Atlantic Sturgeon (*Acipenser oxyrinchus oxyrinchus*) Behavioral Responses to Vessel Traffic and Habitat Use in the Delaware River, USA

by

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Atlantic Sturgeon (*Acipenser oxyrinchus oxyrinchus*) Behavioral Responses to Vessel Traffic and Habitat Preference in the Delaware River, USA

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ABSTRACT

The Atlantic Sturgeon (*Acipenser oxyrinchus oxyrinchus*), a large, long-lived, anadromous species, experienced rapid population declines in later part of the 19th century due to overfishing and habitat loss. The Atlantic Sturgeon was listed under the U.S. Endangered Species Act (ESA) in 2012. Vessel strikes and habitat destruction, along with water quality degradation and bycatch mortality, were listed as major threats to the recovery of the species in the ESA determination.

My study was conducted to further understand behavioral responses of Atlantic Sturgeon to vessel traffic and to indicate habitat preferences within an area of presumed spawning and foraging within the Delaware River. During the spring and summer of 2013 and 2015, I used a VEMCO Positioning System to monitor fine-scale movements of telemetered adult and subadult Atlantic Sturgeon.

I used sturgeon spatiotemporal positions together with, commercial vessel traffic tracking data to observe possible differences between movement types, defined by using trajectory analyses for my first objective. Telemetered adult Atlantic Sturgeon exhibited several behavior types although I found no evidence that these behaviors were influenced by commercial shipping. For my second objective, I modeled habitat use of Atlantic Sturgeon in relation to

Delaware River sediment types to observe whether sturgeons selected different proportions of the sediment than available. While subadults were shown to avoid muddy and sandy sediment, adults preferred course grain sediments (e.g., gravel) and avoided soft sediments (mud and sand). These results support the findings of previous studies which proposed that the study area was likely used for spawning/staging by adults during the early summer months.

My findings suggest that Atlantic Sturgeon exhibit no behavioral responses to vessel presence and that individuals select areas of occupancy based on available sediments. This has direct implications in species conservation due to the continued alteration of sediments to support an increasing vessel traffic through maintenance dredging and channel deepening. If vessel avoidance is not occurring, managers must consider alternative ways of avoiding vessel strikes (e.g., seasonal restrictions such as limits to speed, draft depth, and passing zones) while also considering issues of continued sediment (i.e., habitat) alteration in critical areas of the river.

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CHAPTER 1: ABSTRACT

The Atlantic Sturgeon (*Acipenser oxyrinchus oxyrinchus*) is a large, long-lived species once prolific throughout the Atlantic Coast of North American which was decimated by overfishing and environmental degradation in the late 19th century. The New York Bight Distinct Population Segment, including the Delaware River, was listed as endangered under the Endangered Species Act in 2012. The threat of vessel strikes was listed in the final ruling determination as one of the continued threats to the species existence in several river systems including the Delaware River. My study aimed to quantify behavioral responses of adult Atlantic Sturgeon in the presence of vessel traffic within the Delaware River by deploying a VEMCO Positioning System (VPS) array of hydroacoustic receivers from early spring to late summer of 2013 and 2015. Quantifiable behavioral responses were monitored by measuring angles between successive position estimates to create trajectories. From those trajectories, I developed a categorical representation of behavior type that included type 1 (short clustered time steps), type 2 (large spread out time steps), and type 3 (moderate tortuous combination of large and small time steps). Five adult Atlantic Sturgeon were recorded in 2013, creating a total of 39 trajectories and ten individuals were recorded generating 224 trajectories in 2015. The vast majority of sturgeon positions were located directly in the shipping channel. Three adult females were positioned within the array during both 2013 and 2015. My results demonstrated that there was a significant difference between behavioral types between years but not between instances of vessel presence or absence. Differences between years could be attributable to differences in behavior alone or to the VPS expansion in 2015 from 2013 which monitored different areas of river habitat. The absence of behavioral responses of Atlantic Sturgeon in the presence of vessels suggests that sturgeon do not avoid vessels, cannot hear these vessels, or, if they can, there is not

enough time to react. If there is enough time to react, it is also possible that Atlantic Sturgeon simply are not avoiding vessels even when they can hear/sense them.

CHAPTER 1: INTRODUCTION

The Atlantic Sturgeon (*Acipenser oxyrinchus oxyrinchus*) represents one of 27 globally distributed sturgeons (family Acipenseridae) and one of nine species/subspecies in North America (Cech and Doroshov 2004). Atlantic Sturgeon historically occupied 38 Atlantic Coast riverine systems from the Canadian Maritimes to northern Florida (Vladykov and Greeley 1963). Recent genetic and archaeological findings suggest that Atlantic Sturgeon colonized Europe between 1,200 and 800 years ago wherein it displaced the native European Sturgeon (*A. sturio*) (Ludwig et al. 2002) prior to being extirpated in more recent times. Presently, 20 river systems still support spawning populations of Atlantic Sturgeon along the North American Atlantic coast (ASMFC 2017). As one of the largest sturgeons in North America, Atlantic Sturgeon reaching up 4.3 m in length, achieving a maximum weight of 370 kg (Scott and Crossman 1973) and living to be 60 years (Mangin 1964 cited by Murawski and Pacheco 1977).

Although Atlantic Sturgeon are one of the longest lived anadromous fishes in North America, a combination of late maturity and skip spawning (Van Eenennaam 1998) leads to low lifetime fecundity despite a very high potential fecundity ranging between 0.4 million (Van Eenennaam et al. 1996) and 2.4 million (Ryder 1888) eggs per spawning event. There is a strong latitudinal gradient in maturity schedules and in the mid-Atlantic males mature between 11-12 years and females from 18-19 (Dovel and Berggren 1983). Despite late maturation and infrequent spawning, Atlantic Sturgeon have evolved to endure years of poor habitat conditions while awaiting more suitable spawning and rearing habitats for successful propagation (Secor and Waldman 1999).

Residing in the center of the species' range, the Delaware River historically supported the largest sturgeon fishery in the United States, providing 75% of all Atlantic Sturgeon harvest from

1890-1899, peaking at more than 2,000 metric tons per year (Townsend 1900) and likely supporting the largest population of Atlantic Sturgeon (Secor and Waldman 1999). Following the collapse of the fishery, small-scale commercial harvest continued until a moratorium was implemented almost a century later (ASSRT 2007). A 1998 status review by the National Marine Fisheries Service (NMFS) and United States Fish and Wildlife Service concluded that there was no probable cause to list the species and imposed a 20-40 year moratorium on all Atlantic Sturgeon fisheries until 20 year classes of adult females could be established (NMFS and USFWS 1998).

Atlantic Sturgeon within the Gulf of Maine Distinct Population Segment (DPS) were listed as threatened (USOFR 2012a), and the remaining DPSs including the New York Bight were listed as endangered under the ESA in 2012(USOFR 2012b). Bycatch mortality, water quality degradation, habitat destruction, and vessel strikes were noted as continued threats to the recovery of Atlantic Sturgeon in this final ruling determination. Although directed over-harvest is cited as the largest contributor to the initial decline of Atlantic Sturgeon (Ryder 1888; Vladykov and Greely 1963; Hoff 1980; Smith and Clugston 1997), anthropogenic factors including the loss and modification of habitat, bycatch, impingement/entrainment, and vessel strikes continue to threaten recovery efforts (ASSRT 2007).

Dredging, poor water quality, bycatch, and vessel strikes were also considered major risk factors in determining extinction likelihood of the Atlantic Sturgeon within the Delaware River (Patrick and Damon-Randall 2008). Sturgeons are not only displaced by dredging of the shipping channel (Hatin et al. 2007; Barber 2017) but also have been killed by dredging gear within the Delaware River (Murray 2014). There is also a growing body of evidence that direct mortalities from vessels (i.e., vessel strikes) may be detrimental to the long-term viability of Delaware River

Atlantic Sturgeon (Simpson and Fox 2009; Brown and Murphy 2011). In recent years, the United States Army Corps of Engineers (USACE) has deepened the main shipping channel to 13.7 m from Philadelphia, PA to the Delaware Bay in order to assure safe passage of commercial vessels (USACE, 2016).

Unfortunately for Atlantic Sturgeon populations, international commerce has placed additional focus on shipping and from 1965 to 2003 commercial vessel total gross tonnage increased by a factor of four and the total number of vessels doubled in order to keep up with an ever-increasing demand (National Research Council 2003; Hildebrand 2009). Concomitant with an increase in fleet size and vessel traffic has been an increase in ambient noise (McDonald et al. 2006). This increase in background noise could potentially reduce reaction times of fishes, particularly relevant considering Atlantic Sturgeon benthic feeding and mating behavior which directly places them in the path of large, commercial vessels and the dredged shipping channel (Gilbert 1989; Simpson 2008). Compounding this preference for water types, both sediment and depth are important contributing factors in determining the locations of Atlantic Sturgeon which are known to actively select the navigation channel (Simpson 2008; Breece et al. 2013).

Hearing limitations may also play an important role in the behavioral responses of fish to vessel traffic and, especially in heavily modified river systems, may further contribute to the displacement of fishes (Becker et al. 2013). Particle motion, which determines the hearing abilities of fishes, is determined by a number of factors including distance from the noise source, sediments, and depth of the water (Rogers and Cox 1988; Rogers and Zeddies 2008; Sand and Bleckmann 2008). Fishes use both their inner ear and lateral line for sensing particle motion and directional relation in the water column (Popper et al. 1992). Unlike species which have evolved adaptations for hearing, non-teleost species such as sturgeons lack hearing adaptations such as otoliths used for responding to pressure changes (i.e., sound) (Popper and Fay 1993). Instead, sturgeons' saccule and lagena, two of three otolith organs, are located within a single chamber and, rather than the solid otolith structure present in most teleost species, possess a suspension of calcium carbonite within a gelatinous matrix (Popper 2005). Although sturgeons may be able to localize the source of sound, detection thresholds from the sound origin have not yet been examined (Popper 2005; Meyer et al. 2011). Additionally, male sturgeon have been observed emitting loud, rumbling sounds during times of spawning, a possible indication that sturgeons use sound to communicate (Bruch and Binkowski 2002; Johnston and Phillips 2003). For example, Lake Sturgeon (*A. fulvescens*) and Paddlefish (*Polyodon* spathula), also of the *Acipenseriformes* order, have been reported to be responsive to frequencies between bandwidths from 100 to 500 Hz (Lovell et al. 2005).

Hearing adaptations wherein an "auditory scene" of a surrounding area is constructed, are especially valuable in aquatic systems with poor visibility in order for sensing a given environment, communication, but also for survival (Bregman 1990; Fay and Popper 2000). This auditory scene can be used to avoid predation as well as anthropogenic factors such as the vessels (Fay and Popper 2000). Peak sound pressures of 206 dB re μPa SPL_{peak} or cumulative sound pressures of 187 dB re $\mu Pa^2/s$ SEL_{cum} have been reported as the thresholds of physical damage occurring to fishes (Stadler and Woodbury 2009). More specifically, Lake Sturgeon have been proposed to recognize (hear) sound pressures between 118.1-133 dB (re 1 μPa) at 200 Hz in an environment dominated by sound, similar to that of the heavily-traveled Delaware River (Lovell et al. 2015). This possible hearing range suggests that species similar to Lake Sturgeon should be able to detect commercial vessels, which produce sound levels in the same general range of frequencies (Hz) within a shipping channel (McKenna et al. 2011).

Vessel strikes pose a threat to a broad range of taxa including turtles, (Chaloupka et al. 2008), marine mammals (Laist and Shaw 2006; Williams and O'Hara 2010; Knowlton and Kraus 2001), and fishes including Atlantic Sturgeon (Gutreuter 2003; Simpson and Fox 2007; Brown and Murphy 2010). This is especially true for Atlantic Sturgeon due to the benthic nature of feeding (McLean et al. 2014) and spawning behaviors (Gilbert 1989; Smith and Clugston 1997). Delaware State University (DSU) partnered with the Delaware Division of Fish and Wildlife (DDFW) in an effort to document vessel strikes in 2005. Approximately 200 reported carcasses with over half being attributed to vessel strikes based on a gross examination of wounds have been documented through 2019 (I. Park, DDFW, personal communication). Additional efforts are underway on the James River as managers struggle to understand this developing threat (Balazik et al. 2012). At present, limited information is available to gauge the location of Atlantic Sturgeon vessel strikes and there is little data available about how sturgeon respond in the presence of vessels (Balazik et al. 2012; Barber 2017).

The Delaware River population of Atlantic Sturgeon declined from the largest in the species' range (Secor and Waldman 1999) to bordering on extirpation although recent evidence of spawning success is a positive sign. Recovery may also be hampered or stopped by threats such as vessel strikes (Brown and Murphy 2012; ASMFC 2017), a phenomenon confirmed by regular reports of subadult and adult sturgeon carcasses within the Delaware River and bay. My study aims to identify areas of overlap between vessels and Atlantic Sturgeon and to quantify whether or not sturgeon alter behavior in the presence of vessel traffic. In doing so, I hope to elucidate behavioral responses which can be used not only within the Delaware River estuary but also in similar systems and species. This information is critical for understanding the nature of sturgeon/vessel interactions and is required for managers to develop measures in order to assure both the recovery of the species and regional economic success (Knowlton and Kraus 2001).

CHAPTER 1: METHODS

Study Area

The Delaware River is the longest undammed river east of the Mississippi and provides approximately 5% of the nation's drinking water (Kaufman et al. 2010). My study was conducted within the Delaware River near Chester, PA near river kilometer (rkm) 130 which has been heavily modified for shipping (USACE 2016) with a channel comprised mainly of non-depositional and mixed-grain reworking sediments (Sommerfield and Madsen 2003). These descriptors, along with the narrowness of the river and steep gradient away from the channel into soft bottom sediments (i.e., unsuitable for sturgeon spawning), created a suitable study area to observe fine-scale movements of Atlantic Sturgeon in an area with high levels of commercial vessel traffic. This portion of the river was also chosen because previous studies have indicated likely spawning and or aggregating of adult Atlantic Sturgeon (Simpson 2007; Breece et al. 2013).

Telemetry Array

A VEMCO Positioning System (VPS) array comprised of 20 passive hydroacoustic receivers (VEMCO, Ltd. VR2W) was deployed along the perimeter of the shipping channel within the Eddystone and Chester Ranges of the Delaware River between rkm 132-138, in the vicinity of Chester and Little Tinicum Islands in a 5.2 km corridor (Figure 1-1) between April 9 and 18, 2013 and expanded to 26 passive receivers between rkm 131-138 along a 6.5 km corridor close to the section utilized in 2013 from July 13 and 22 (Figure 1-1). The study area was increased in 2015 to better account for individuals positioned just outside the array in the first year of study.

The VPS utilizes hyperbolic positioning to measure differences in detection times at pairs of acoustic receivers which is then converted into distances of telemetered individuals from receiving stations (Smith, 2013). Due to the method of hyperbolic position calculation, a unitless measure of error, horizontal positioning error (HPE) is calculated and ascribed to each position. Each receiver was accompanied by a transmitter (VEMCO, Ltd. V16) with a nominal transmission delay of 60 s (range = 30-90 s) in order to synchronize neighboring pairs of receivers and reduce detection error (Smith 2013). Each of the receiver/transmitter pairs were moored with a 36 kg concrete block designed to keep the receivers upright in the current (Figure 1-6). An additional 1.8 kg Danforth anchor was connected to the mooring via a 31m sink rope, which allowed for recovery by grappling. Prior to deployment, I conducted a range test for five days with eight receiver/transmitter moorings, spaced approximately 600 m apart, to determine detection efficiencies and array configuration.

Collection of Atlantic Sturgeon

Atlantic Sturgeon were collected between three and 15 km off the Delaware coast near the Delaware/Maryland border. For detailed procedures regarding the capturing, handling, and surgical procedures of Atlantic Sturgeon off the coast of Delaware, see Breece et al. (2013). Additionally, tagging of adult and subadult sturgeon occurred along other parts of the Atlantic coastline with each tag owner identified through the collaborative Atlantic Coast Telemetry Network.

<u>Analyses</u>

Telemetry

Individual telemetered Atlantic Sturgeon that moved into in the VPS array were screened by their HPE in order to estimate location precision. Positions were filtered by HPE < 50 (Smith 2013) in order to remove position estimates with poor granularity (i.e., outside of position triangulation) as has been done in similar telemetry studies (McLean et al. 2014). Array occupancy time for each Atlantic Sturgeon was calculated for 2013 and 2015 by dividing the total number of active array days by the number of individual days an individual generated useable position estimates (Table 1-4). Position estimates were imported into R software, and both temporally and geographically referenced using the '*adehabitatLT*' package (Calenge 2011). Due to HPE values being greater than 50, a total of 79 sturgeon positions were removed from analysis (37 in 2013 and 42 in 2015).

Vessel Movement

Vessels > 20 m in length were tracked through the mandatory Automatic Identification System (AIS) and archived by the Maritime Exchange in Philadelphia, PA. These data were plotted using geographic information systems software (QGIS Geographic Information System version 2.18.28 (2018)) and R (R Development Core Team 2010) to provide course tracks through the study site. Vessel category types, determined by overall size and cargo, were assigned to all vessels passing through the array. For the purposes of this study, vessel types, defined by the United Nations Conference on Trade and Development (2008), were categorized as general cargo, petroleum carriers, tugs, and miscellaneous (e.g., yachts, law enforcement, etc.).

Individual Atlantic Sturgeon trajectories were compared between periods with and without vessels within the probable range of sturgeon being able to detect vessels in the study area. I estimated a general detection range of vessels by sturgeon by using the locations of my upper and lowermost receivers and adding a buffer of 520 m in order to account for a vessel being detectable. This buffer size was based on the hearing limitations of Lake Sturgeon in freshwater, estimated to be 133 dB (Meyer et al. 2010; Lovell et al. 2015), and the maximum noise for commercial vessels, a container vessel (188.1 dB) (McKenna et al. 2012). In addition to tracking and categorizing vessel traffic, I also quantified the number of 'transits', defined as a vessel passing through the array with the same minimum speed threshold, in both study years. This was accomplished by segmenting total monitored array time into two-hour segments. I used two hours as the limit to determine a segment based on AIS data which indicated that no vessels travelling above 0.5 m/s were recorded more than once in a two hour period.

Sturgeon/Vessel Interactions

Atlantic Sturgeon position estimates were plotted using the *adehabitatLT* package (Calenge 2011) in R (R Development Core Team 2010) in an attempt to quantify individual behaviors. I used angular measurements between movements of fine-scale trajectories of Atlantic Sturgeon, characterized as unique trajectory 'bursts', defined as a grouping of at least five successive spatiotemporal position relocations (i.e., a temporally referenced geospatial position estimates derived from acoustic telemetry) within a set amount of time, in order to compare distinct, continual sturgeon movement tracks through R package *'adehabitatLT'* (Calenge 2011). I used the average speed of all vessels in both years within the averaged array distance between years to create an approximated array travel time of 1497 s. This time step was used to distinguish how many seconds could pass between successive positions before a new trajectory was created.

I then employed this time step, as opposed to some iterations of the acoustic tag's minimum delay (e.g., 120 s) in order to better fit the study area's level of vessel traffic. Once a vessel was first recorded, it would have 1497 s, on average between 2013 and 2015, to completely pass through the array. I hypothesized that this larger time step would not add superfluous position estimates to a trajectory because adult Atlantic Sturgeon, possibly using this area for staging/spawning, would utilize the area for large amounts of time and this would allow for greater behavioral characterization of angular movements. These minimum time limits between successive position estimates allowed me to create standardized trajectories for each animal. For each trajectory, the absolute angle (angle between x direction and the next step of the relocation), relative angle (turning angle), distance, and time between two positions was calculated.

I also calculated linearity ratio and rate of movement (Calenge et al. 2009; Heupel et al. 2012) for telemetered Atlantic Sturgeon trajectories. Each variable's mean, standard deviation, and sums of distance (m) as well as time (s) were calculated for all trajectory bursts. Trajectory burst variables were categorized between years and vessel presence (P) or absence (N) in the array. In order to quantify discernable movement behavior types, I removed highly correlated variables and analyzed unique dependent movement metric variables by using the R package 'corrplot' (Wei 2012). I created several correlation matrices, each time removing correlated variables, coefficient value > 0.30, until only non-correlated variables remained. I used a principal component analysis (PCA) to observe how these variables interacted and to discern the number of data clusters, which were classified into discrete behaviors.

To further discern the number of clusters, I also ran a within sum of squares (WSS) analysis to validate the number of clusters for the K-mean cluster analysis. The Elbow Method was used to determine that there were three data clusters by evaluating the sum of squared errors by plotting against K. This method distinguishes the number of data clusters by segmenting the plotted sum of squares at the point where K has diminishing returns. I assigned each trajectory burst to a cluster category, defined as movement type 1, type 2, and type 3, before using a multivariate analysis of variance (MANOVA) to identify variables significantly influencing the determination of clusters before finally employing a chi-square test by both year and vessel presence or absence in the array. An alpha value of 0.05 was used for all statistical tests.

I took a stepwise approach in attempting to understand (1) whether Atlantic Sturgeon can hear vessels, (2) if they can, whether they hear them through the river system's background noise, (3) whether the species' minimum hearing threshold allows for adequate reaction time, (4) whether there is a minimum threshold to response (avoidance) time, and (5) if all of these are met, whether the sound of a vessel elicits a response from sturgeon.

CHAPTER 1: RESULTS

Telemetry

Atlantic Sturgeon were almost exclusively relocated within the shipping channel (Figures 1-2, 1-3) in areas of direct overlap with vessel traffic (Figures 1-4, 1-5) in both 2013 and 2015. More specifically, Atlantic Sturgeon were most often relocated along the outer edge of the channel along the western and northwestern sections.

Between April 13 and July 9, 2013 five individual adult Atlantic Sturgeon were detected within the 5.2 km (6.4 km with buffer) VPS array (Tables 1-1, 1-2) which, due to the requirements of positioning, were located largely in the confines of my array (Figure 1-2).

Amongst these adults, 39 total trajectory bursts were recorded and used for analysis. Individual adult Atlantic Sturgeon were first located within the VPS array between April 4 and June 7, 2013 and last located between May 27 and June 8, 2013. Mean array time occupancy for adult Atlantic Sturgeon in 2013 was 0.06 days (range = 0.01 – 0.21 days) (Table 1-2).

The 2015 sampling season took place between April 18 and July 9 over a 6.5 km stretch of river and detected 10 adults Atlantic Sturgeon (Tables 1-1, 1-3) limited to the array area (Figure 1-3) totaling 224 trajectory bursts. Of these 10 adults a total of three were returning individuals, all females, from 2013. Individual Atlantic Sturgeon were first detected between May 8 and June 12, 2015 and last observed between May 8 and June 18, 2015. Mean array occupancy of adult Atlantic Sturgeon during the 2015 VPS was calculated to be 0.09 days (range = 0.01 – 0.21 days) (Table 1-3).

Vessel Movement

A total of 2,991 transits (range = 19–65 per day, mean = 38.3 per day) made by 307 unique vessels were recorded with AIS transponders over the course of the 78 study days in 2013. The majority were made by tug boats with 1,822 transits (60.9%) followed by general cargo with 610 (20.4%), petroleum carriers made 346 (11.6%), and finally miscellaneous vessels made 213 (7.1%) in 2013 (Table 1-5). General cargo vessels were the most common vessel (n=150; 37.8%), followed by petroleum carriers (n=99; 24.9%), then tugs (n=108; 27.2%) and the remainder (n=40; 10.1%) were miscellaneous vessels (Table 1-5). Vessels monitored via AIS transponder averaged 4.8 m/s (range = 0.5–30.3), or about 17 km/hour, while moving at least 0.5 m/s inside the VPS array in 2013.

Throughout the 77 days of activity of the 2015 VPS array, 440 unique vessels made 3,609 transits (range = 2–71 per day, mean = 50.2 per day), comprising 177 (40.2%) general cargo, 88 (20.0%) petroleum carriers, 106 (24.1%) tugs, and 69 (15.7%) miscellaneous vessels (Table 1-5) transits. Vessels monitored via AIS transponders averaged 4.4 m/s (range = 0.5–20.2), or about 16 km/hour, while moving at least 0.5 m/s inside the VPS array. The majority in 2015 were made by tugs with 2,332 transits (64.6%) followed general cargo with 677 (18.8%), miscellaneous vessels made 353 (9.8%), and finally petroleum carriers made 246 (6.8%) in 2015 (Table 1-5). Vessels transited through the array a maximum of 72 times per day (mean = 50 transits per day) in both study years.

Sturgeon Vessel Interactions

Using a predetermined time steps of 1497 s, a total of 244 adult Atlantic Sturgeon trajectory bursts were identified and used for further analysis. The mean distance (mean = 150 m), mean time (mean = 345.7 s), mean relative angle (mean = 0.01 radians), mean absolute angle (mean = -0.28 radians), mean rate of movement (mean = 0.55 m/s), linearity ratio (mean = 0.56), standard deviation of distance (mean = 117.1 m), standard deviation of time (mean = 275.2 s), standard deviation of relative angle (mean = 1.17 radians), standard deviation of absolute angle (mean = 1.61 radians), and standard deviation of the rate of movement (mean = 0.26 m/s) were calculated for each trajectory burst.

Of the eleven dependent variables (trajectory burst metrics), all but five were strongly correlated (correlation coefficient values > 0.30) and removed from further analysis to reduce codependent relationships. The variables linearity, mean time, mean absolute angle, mean relative angle, and standard deviation of the absolute angle were retained for further analyses (Figure 1-7).

The PCA indicated the proportion of variance for each of the five remaining variables (linearity = 0.27, mean time = 0.23, mean relative angle = 0.19, mean absolute angle = 0.18, standard deviation of absolute angle = 0.14). The K-cluster mean analysis identified three clusters for further analysis (Figure 1-8). The MANOVA indicated that mean trajectory burst time ($P < 0.01$) was the only significant driver of the three cluster types while linearity ($P = 0.10$), mean absolute angle ($P = 0.49$), mean relative angle ($P = 0.34$), and standard deviation of the absolute angle ($P = 0.65$) were not significant determining metrics (Figure 1-9).

For adult Atlantic Sturgeon, type 1 trajectories averaged 193 s, type 2 averaged 540 s, and type 3 averaged 332 s (Figure 1-10). Type 1 movements were composed of short, clustered steps over a short time step indicating more rapid movements, type 2 has large time steps between relocations, suggestive of meandering or infrequently relocations, and type 3 had had moderate time steps between relocations, tortuous in nature with a combination of closely spaced and relatively large distances between steps. An examination of these trajectories by the chi-square test documented a significant difference between year and movement type ($P < 0.01$) (Table 1-6). Roughly 75% of the 39 trajectories in 2013 fit movement type 1, 5% fit movement type 2, and 20% fit movement type 3 while 28% fit movement type 1, 36% fit movement type 2, and 37% fit movement type 3 in 2015. Importantly, I found no significant difference between periods of vessel presence/absence and sturgeon movement types (i.e. cluster types) ($P = 0.90$) (Table 1-6). When vessels were not present, roughly 38% fit movement type 1, 31% fit movement type 2, and 31% fit movement type 3 while 35% fit movement type 1, 30% fit movement type 2, and 35% fit movement type 3 when vessels were not present.

Returning Adult Females

Three adult females (tag identification numbers 46237, 48785, and 30494) were located within the array in both 2013 and 2015. 46237 created 851 spatiotemporal positions and 19 trajectory bursts, primarily of movement type 1 (73.7%) in 2013 but was only located 11 times creating two trajectory bursts of movement type 2 only in 2015 and these movement types significantly differed between years ($P < 0.01$). 48785 followed a similar pattern having been relocated 434 times with 11 trajectory bursts, primarily of movement type 1 (81.8%) in 2013 but was only located 24 times creating four trajectory bursts in 2015 (movement type 2 (75.0%)) and these movement types significantly differed between years ($P < 0.01$). 30494 was only relocated 84 times in 2013 creating five trajectory bursts, exhibiting behaviors mainly of movement type 1 (80.0%) and was located six times, creating one trajectory of movement type 3 and movement types did not significantly differ between years ($P = 0.34$).

CHAPTER 1: DISCUSSION

Commercial shipping is an almost constant feature of the Delaware River from Wilmington, DE up through the northern side of Philadelphia, PA. These vessels affect biota within the river system both directly (e.g., physically displacing and mortality) and indirectly (e.g., channel maintenance affecting sediment types, water quality changes, etc.). Dredging and vessel presence have been shown to cause differences in Atlantic Sturgeon spatial distribution in the nearby James River, VA, possibly indicating avoidance behavior (Barber 2017).

This study's VPS array was increased southward by 1.3 km from 2013 to 2015 due to the detection of additional Atlantic Sturgeon during the 2013 field season that were outside the positioning field for the VPS array. This area, adjacent to the Marcus Hook Anchorage, is presumed to be a likely feeding location for juveniles/subadults but also possibly a staging area of adults prior to spawning (Simpson 2008; Breece et al. 2013). Increasing the array further south greatly added to the total number of subadult and adult position estimates. As a result of an increase of approximately 25% in the second year of my study, it was not possible to directly compare the number of positions or occupancies of sturgeons between study years. However, I was able to compare behavioral responses (movement types) between years since these are not defined by the relative size of the area, especially since the array mostly overlapped between years. I hypothesize that the significant difference between yearly behaviors either occurred because of changes to environment (e.g., sediment composition, temperature, and/or flow alteration due to maintenance dredging) or due to differences between yearly array areas (e.g., sediment compositions were different between study areas).

My findings suggest that adult Atlantic Sturgeon behaviors can be classified into three primary movement types in the Delaware River, defined by the average time between successive spatiotemporal position relocations for a trajectory burst. Movement type 1, indicating rapid movement through the river, made up the majority of behavioral characteristics within this portion of the river. Using these behavioral classifications, I found little support that Atlantic Sturgeon exhibit a behavioral response to vessel traffic in the Delaware River. My findings may be the result of resolution limitations in my study system or the fact that Atlantic Sturgeon are not actively sensing and/or avoiding vessels in an area of dense vessel traffic and high ambient noise. While Atlantic Sturgeon are almost constantly exposed to vessels passing overhead/around their location as evidenced by the high levels of vessel traffic, it is difficult to quantify a fine-scale relationship.

Interestingly, the only returning individuals in both years of the study were adult females. Two of the three returning adult female Atlantic Sturgeon exhibited significantly different movement types between years. Each was relocated more, primarily exhibiting a small time step between locations (movement type 1) in 2013 and much longer time steps with fewer locations (movement type 2) in 2015. Rapidly occurring, successive relocations with little distance between each point indicates that these individuals likely occupied the array continuously. In contrast, very large time steps, typically with fewer relocations over a longer period of time could indicate that these individuals were travelling quickly, covering large distances within the study area. The observed differences between 2013 and 2015 could therefore indicate that these two adult females were exhibiting spawning and/or staging behavior within and/or around the VPS array in 2013 but returned in 2015, only spending limited time within the array. Alternatively, it is possible that the activity of these two sturgeons was simply not captured within the tight geographic parameters of the acoustic array.

The 2012 ESA listing of Atlantic Sturgeon in the New York Bight DPS as endangered identified vessel strikes, as a continued impediment to the species' recovery (USOFR 2012b). An egg per recruit analysis also suggested that an annual mortality rate greater than 2.5% of total female Atlantic Sturgeon, such as the loss due to vessel strikes, would be detrimental to the overall population (Brown and Murphy 2011). The trend of vessel strikes in the face of increasing commerce needs from the Delaware River ports is not dissipating. There have been more than 200 Atlantic Sturgeon carcasses reported in the Delaware Estuary from 2005 through 2019 (I. Park, DDFW, personal communication) of which 54% were determined to have been caused by vessel strikes. Assuming this total can be similarly expanded by the 30% carcass recovery success proposed by Balazik et al. (2012) in the James River, just under 400 Atlantic Sturgeon have been killed in Delaware River since the carcass recovery program began.

The Delaware River serves as the economic lifeblood of the tristate area contributing $25 billion annually towards a range of activities while providing approximately 600,000 jobs to the region (Kauffman 2011). Hundreds of individual vessels, ranging between small tugs and large petroleum carriers and general cargo ships, navigated throughout this small section of the

Delaware River. Ambient noise, one of the inherent effects of vessel traffic, especially of large vessels, likely dampens avoidance effectiveness in aquatic species, which has been best studied in marine mammals (e.g. Bottlenose Dolphin (*Tursiops truncatus*)); a specialized listener of underwater noises (Fouda et al. 2018). Even though Atlantic Sturgeon do not share the same hearing sensitivity and reliance as that of marine mammals (Popper 2005), ambient noise further reduces the already limited sensitivity of sturgeons to other sounds within the system. While adult Atlantic Sturgeon are not at risk of predation while in the rivers due to their large size, lacking an auditory perception of their environments exacerbates their lack of evolutionary hearing traits. When not able to detect, and therefore avoid vessels, the risk of vessel interactions is at its highest. Atlantic Sturgeon have been around for ~200 million years (Bemis and Kynard 1997) while vessel traffic has only posed a threat since the main dredging of the Delaware River was completed in 1898 (Moore 1908). Along with human modifications to the river, Atlantic Sturgeon were severely overfished in the Delaware River in the late 1800's, eventually leading to a collapse of the population, thus landings (Cobb 1900).

Using historic lessons from similar studies of sea turtles (Chaloupka et al. 2008;), marine mammals (Laist and Shaw 2006; Williams and O'Hara 2010; Knowlton and Kraus 2001), and fishes (Gutreuter 2003), wherein seasonal restrictions (e.g., speed, draft depth, navigation restrictions, etc.) to commercial vessel traffic are/were enforced, it is important for resource managers to consider what, if anything, can be done to minimize the risk to Atlantic Sturgeon recovery. Since vessel speed has been identified as a major risk to large aquatic species such as whales (Laist et al. 2001), voluntary speed restrictions, management area designations, and proximity limitations are conservation measures put in place for the North Atlantic Right Whale (*Eubalaena glacialis*), another imperiled species (USOFR 2013). While obviously a much different species, suggestions put forth to adjust/restrict vessel traffic are also applicable in the case of the Atlantic Sturgeon. Many of the exclusion zones, specifically calving areas, of the North Atlantic Right Whale occur in the ocean (USOFR 2013), a much more open area compared to the Eddystone and Chester Ranges of the Delaware River. Due to the acute bend within this section of the Delaware River, vessels require a sustained level of speed thus; speed restrictions may not be the most effective management measure.

Regulation changes to commercial shipping traffic, a vitally important component of the region's economy will be difficult considering that the USACE has already spent more than $400 million on channel maintenance and deepening from 12.2 to 13.7 m since 2008 (USACE 2016). Voluntary restrictions of commercial and recreational vessels, as have been established for North Atlantic Right Whales, can easily be disregarded. Another approach could be that of the West Indian Manatee (*Trichechus manatus latirostris*) in Florida where mandatory speed, area, and activity restrictions are employed throughout shallow reaches of smaller tributaries where vessel strikes are more common (USFWS 2001). Compliance studies indicate that enforcement presence is key in assuring higher compliance (Shapiro 2001; Gorzelany 2004). The Eddystone and Chester Ranges of the Delaware River host much larger, commercial (i.e., not private) vessels travelling in deeper water than the enforced systems of Florida, likely making management and enforcement more difficult. However, protection of manatees in Florida is possible due to areas of interaction being clearly identified and enforced. My findings illustrated the presence of telemetered adult Atlantic Sturgeon along the western and northwestern outer edges of the shipping channel which overlap with regions of high vessel traffic suggesting an increased risk of vessel interactions. Therefore, it could be much more meaningful for seasonal restrictions of shipping to avoid the western and northwestern edge of this channel during times of presumed spawning. This would not only require seasonal restrictions to a portion of the shipping channel but would likely also necessitate no passing zones due to the narrowness of the river.

Similar to studies of Lake Sturgeon in the Mississippi River (Gutreuter et al. 2003) and Atlantic Sturgeon in the James River (Balazik 2012; Barber 2017), my findings suggest that sturgeons lack the ability to avoid vessel traffic . Although sturgeons appear to locate and avoid intense sound near their tolerable limit in the Hudson River (Krebs et al. 2015; Krebs et al. 2016), the species is not likely responsive to many anthropogenic factors but this phenomenon is simply more apparent in a heavily trafficked river such as the Delaware River. Future use of fine-scale telemetry studies in similar river systems could be used to bolster this study's findings.

Ultimately, resources managers need to find ways to mitigate and/or reduce the number of Atlantic Sturgeon vessel strikes in the Delaware River if the goal of the ASMFC and NMFS to recover the species to a point that will allow sustainable harvest of the species is to be achieved. Although sustainably harvesting Delaware River Atlantic Sturgeon is likely a hefty futuristic goal, this prospect is likely trivial when compared to the economic importance of the Philadelphia Port System. Although it is unlikely a sustainable sturgeon fishery will provide real economic incentives, especially in the face of a local economic driver like the Delaware River port system, it is important to consider the historic role of this regions' fishery in the development of our nation and how we should leverage any and all means to foster conservation and recovery of this imperiled species.

Table 1-1. Summary of adult Atlantic Sturgeon tag number, associated research institute of tag, date tagged, length (FL/TL), sex, and total number of positions estimates in both study years (2013/2015) within the VPS array.

Tag ID Number	Organization	Release Date	FL (cm)	TL (cm)	Life Stage	Sex	Position Estimates 2013	Position Estimates 2015
11615	DSU	4/5/2009	176	203	Adult	Male	16	-
20458	DSU	4/25/2011	186	211	Adult	Unknown	-	9
46237	DSU	4/2/2011	208	230	Adult	Female	851	11
48761	DSU	4/12/2010	184	208	Adult	Male	55	-
48763	DSU	4/12/2010	196	223	Adult	Female	-	128
48785	DSU	4/22/2010	206	230	Adult	Female	434	24
25370	DSU	4/26/2014	191	210	Adult	Male	-	53
26428	DSU	4/12/2014	174	196	Adult	Male	-	430
27520	DSU	4/26/2013	177	201	Adult	Unknown	-	627
30447	DSU	4/3/2012	167	188	Adult	Male	-	364
30469	DSU	4/9/2012	208	233	Adult	Female	-	405
30494	DSU	4/17/2012	172	193	Adult	Female	84	6

Table 1-2. Detection frequency of acoustically tagged adult Atlantic Sturgeon within the Delaware River indicating how many times each individual was positioned, total days in which each individual was positioned within the array, the total array occupancy (days present divided by total array days), the first and last date, and the number of total trajectory bursts recorded in 2013. The sum, mean, and standard deviation (STDV) were also calculated.

Transmitter	Detection Frequency	Unique Days in Array	Array Occupancy (Days)	Date Entered	Date Departed	Burst Frequency
11615	15	2	0.03	6/7/2013	6/8/2013	2
46237	851	7	0.09	5/22/2013	5/28/2013	17
48761	57	3	0.04	4/29/2013	5/27/2013	2
48785	413	4	0.05	5/24/2013	5/31/2013	11
30494	85	4	0.05	5/2/2013	6/8/2013	5
Sum	**1421**	**20**	**0.26**			**39**
Mean	**269.43**	**4.43**	**0.06**	**5/17/2013**	**6/1/2013**	**7.40**
STDV	**354.13**	**1.87**	**0.02**			**6.50**

Table 1-3. Detection frequency of acoustically tagged adult Atlantic Sturgeon within the Delaware River indicating how many times each individual was positioned, total days in which each individual was positioned within the array, the array occupancy (days present divided by total array days), the first and last date time, and the number of total trajectory bursts recorded in 2015. The sum, mean, and standard deviation (STDV) were also calculated.

Transmitter	Detection Frequency	Unique Days in Array	Array Occupancy (Days)	Date Entered	Date Departed	Burst Frequency
20458	9	1	0.01	6/1/2015	6/1/2015	2
46237	11	2	0.03	5/18/2015	5/21/2015	2
48763	128	4	0.05	5/17/2015	5/20/2015	13
48785	24	4	0.05	5/31/2015	6/10/2015	4
25370	53	4	0.05	6/12/2015	6/18/2015	8
27520	628	16	0.21	5/14/2015	6/10/2015	55
30447	365	12	0.16	5/14/2015	5/29/2015	35
30469	406	10	0.13	5/11/2015	5/20/2015	26
30494	6	1	0.01	5/8/2015	5/8/2015	1
Sum	**1630**	**66**	**0.86**			**224**
Average	**181.11**	**6.60**	**0.09**	**5/20/2015**	**5/29/2015**	**18.67**
STDV	**228.38**	**5.40**	**0.07**			**17.09**

Table 1-4. Comparison of total array occupancy and number of detections of adult Atlantic Sturgeon between 2013 (n=5) and 2015 (n=10). The mean and standard error were also calculated for occupancy and number of detections in each year.

	Occupancy		Detections	
Year	Mean (Range)	Standard Error	Mean (Range)	Standard Error
2013 (n=5)	0.05 days (0.03-0.09 days)	0.01	284 (15-851)	76.13
2015 (n=10)	0.08 days (0.01-0.21 days)	0.26	181 (6-628)	158.37

Table 1-5. Total individual vessel types and vessel transits through the Eddystone and Chester Ranges of the Delaware River in 2013 and 2015. The total number of vessels and vessel transits was summed for each year.

	Individual Vessels		Vessel Transits	
Vessel Type	2013	2015	2013	2015
General Cargo	150 (37.8%)	177 (40.2%)	610 (20.4%)	677 (18.8%)
Petroleum Carriers	99 (24.9%)	88 (20.0%)	346 (11.6%)	246 (6.8%)
Tug	108 (27.2%)	106 (24.1%)	1,822 (60.9%)	2,332 (64.6%)
Miscellaneous	40 (10.1%)	69 (15.7%)	213 (7.1%)	353 (9.8%)
Sum	397	440	2,991	3608

Table 1-6. Summary of adult Atlantic Sturgeon trajectory clusters by year and vessel presence. (**) denotes statistical significance at $\alpha = 0.05$.

	Vessel Presence		**Year	
Cluster	No	Yes	2013	2015
1	17	63	29	51
2	14	54	2	66
3	14	62	8	68

Table 1-7. Summary of adult Atlantic Sturgeon movement types within the Delaware River in 2013 and 2015.

Movement Type	Description
1	short, clustered time steps between relocations
2	large time steps between relocations
3	moderate, tortuous combination of large and small time steps between relocations

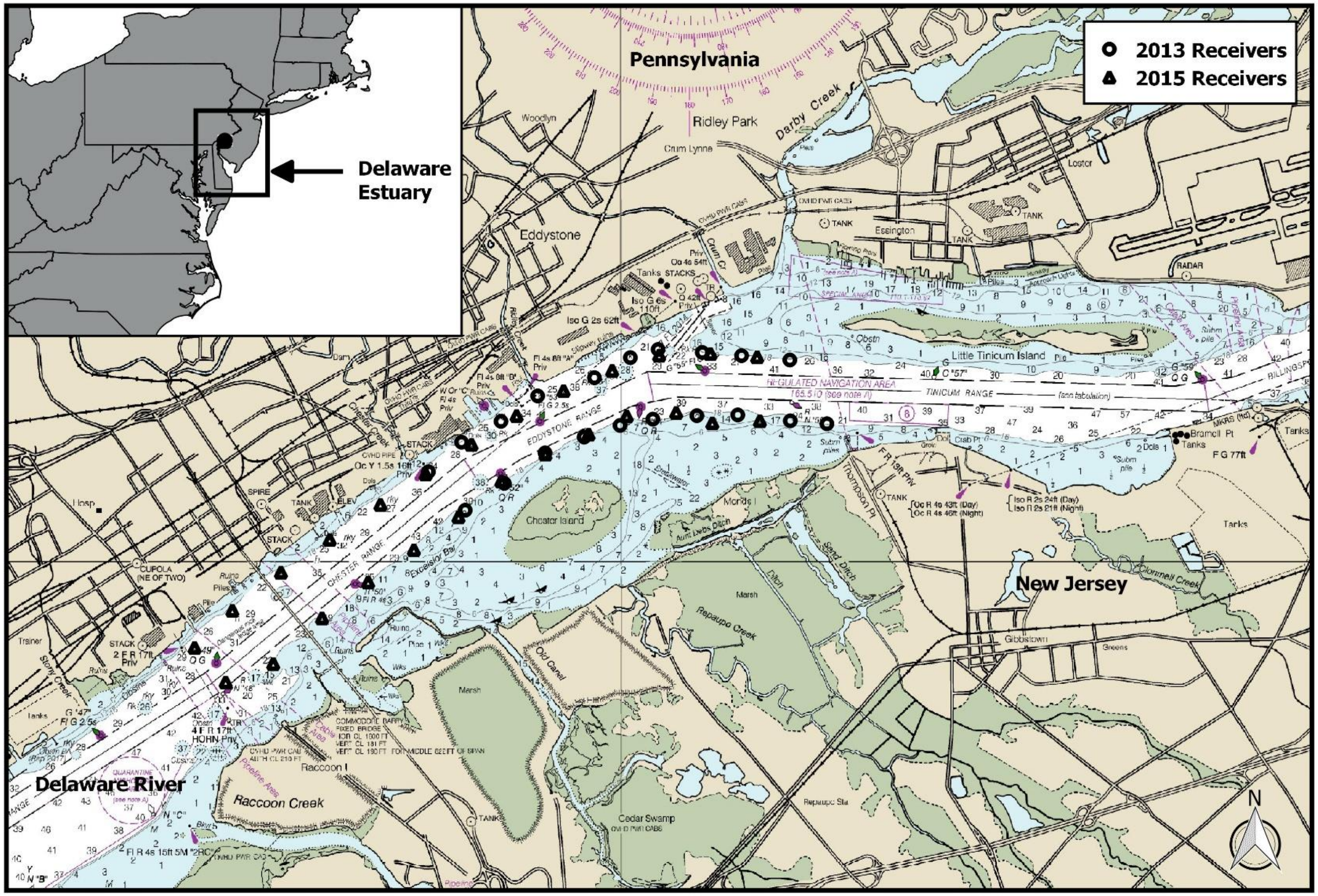

Figure 1- 1. 2013 and 2015 study site of VPS arrays: Delaware River bathymetry near Chester, PA. Inset details locations of VEMCO, Ltd. VR-2W hydroacoustic receivers and accompanying transmitter tags.

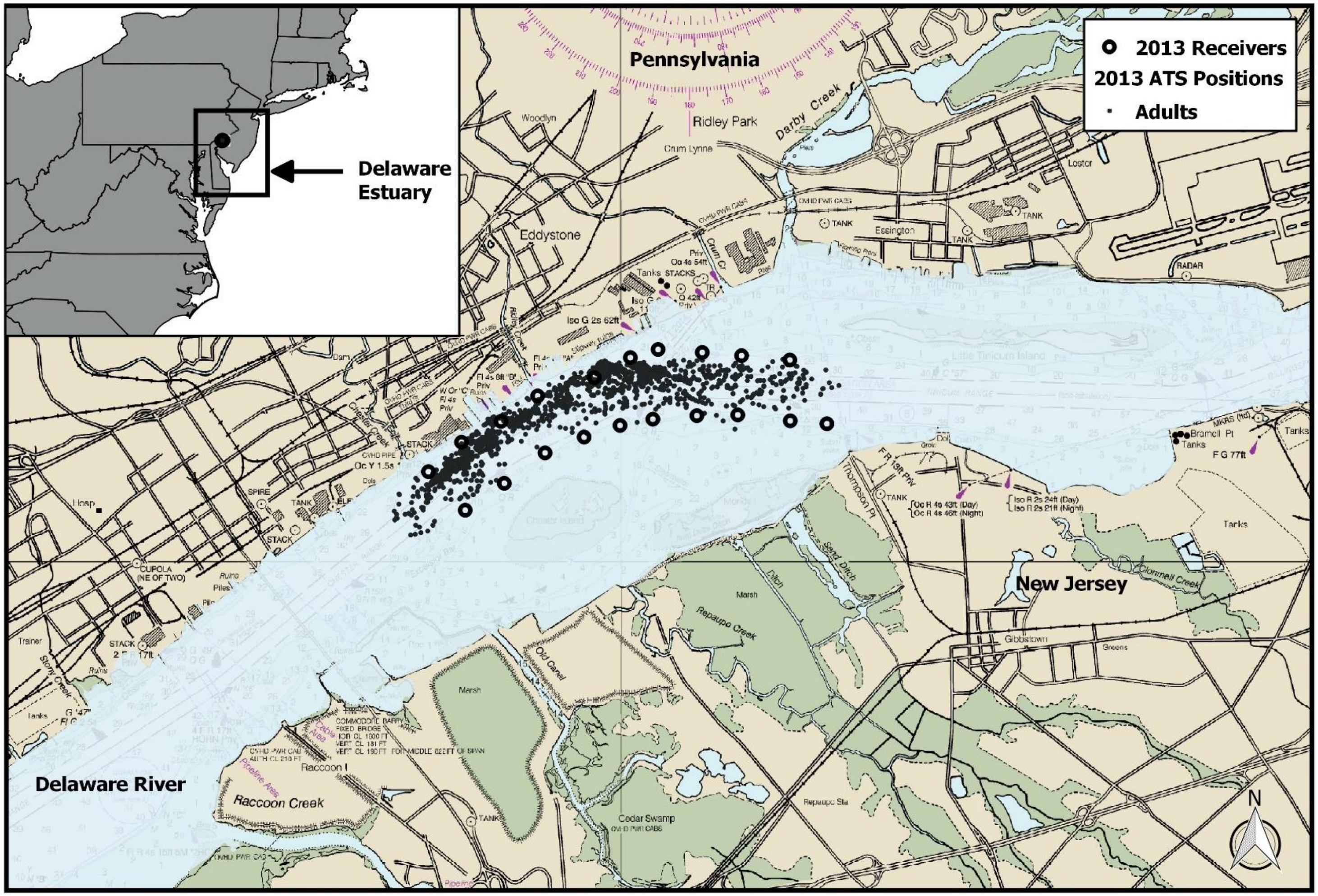

Figure 1- 2. 2013 VPS array overlaid with adult Atlantic Sturgeon position estimates, filtered to only include position estimates used in trajectory analysis.

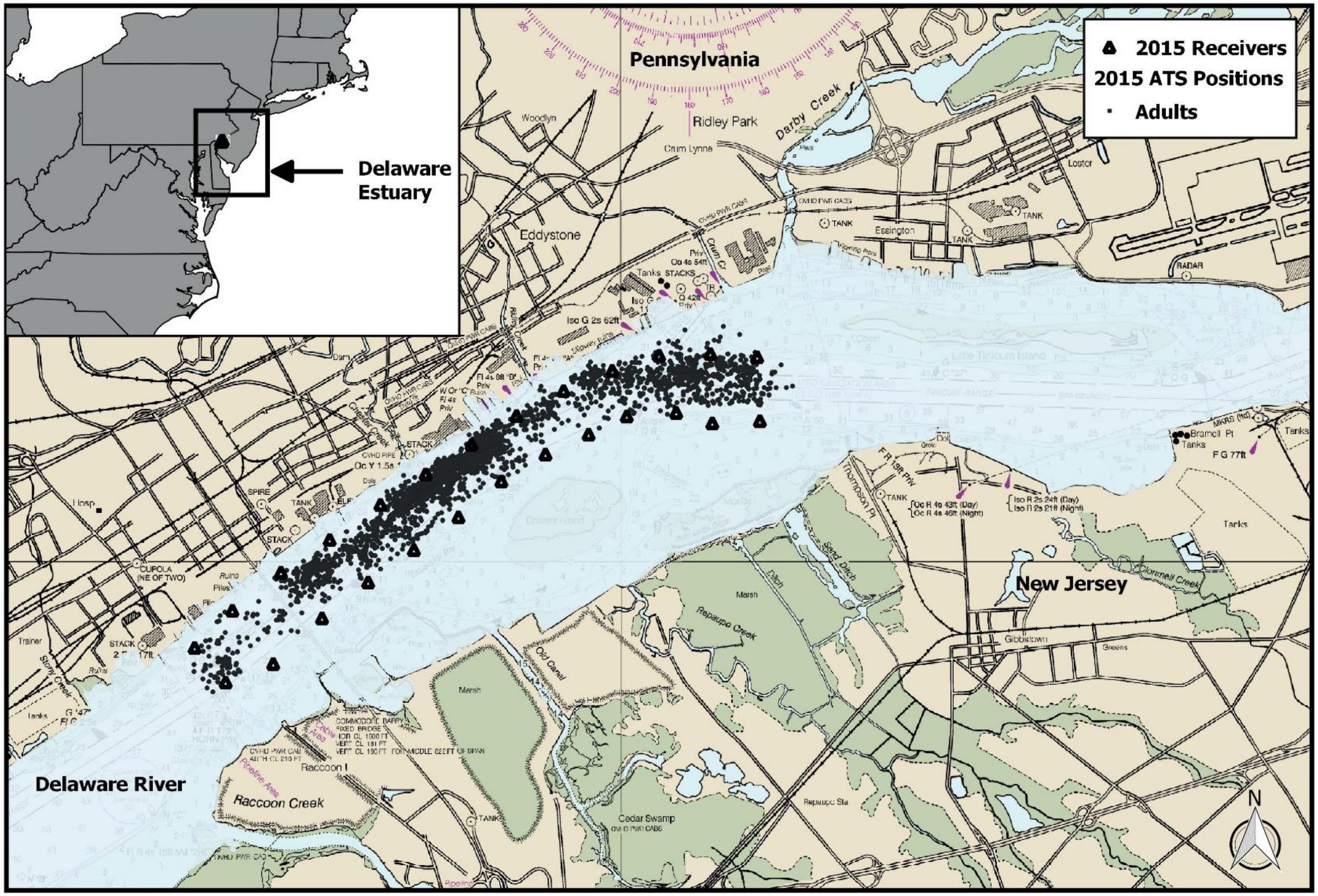

Figure 1- 3. 2015 VPS array overlaid with adult Atlantic Sturgeon position estimates, filtered to only include position estimates used in trajectory analysis.

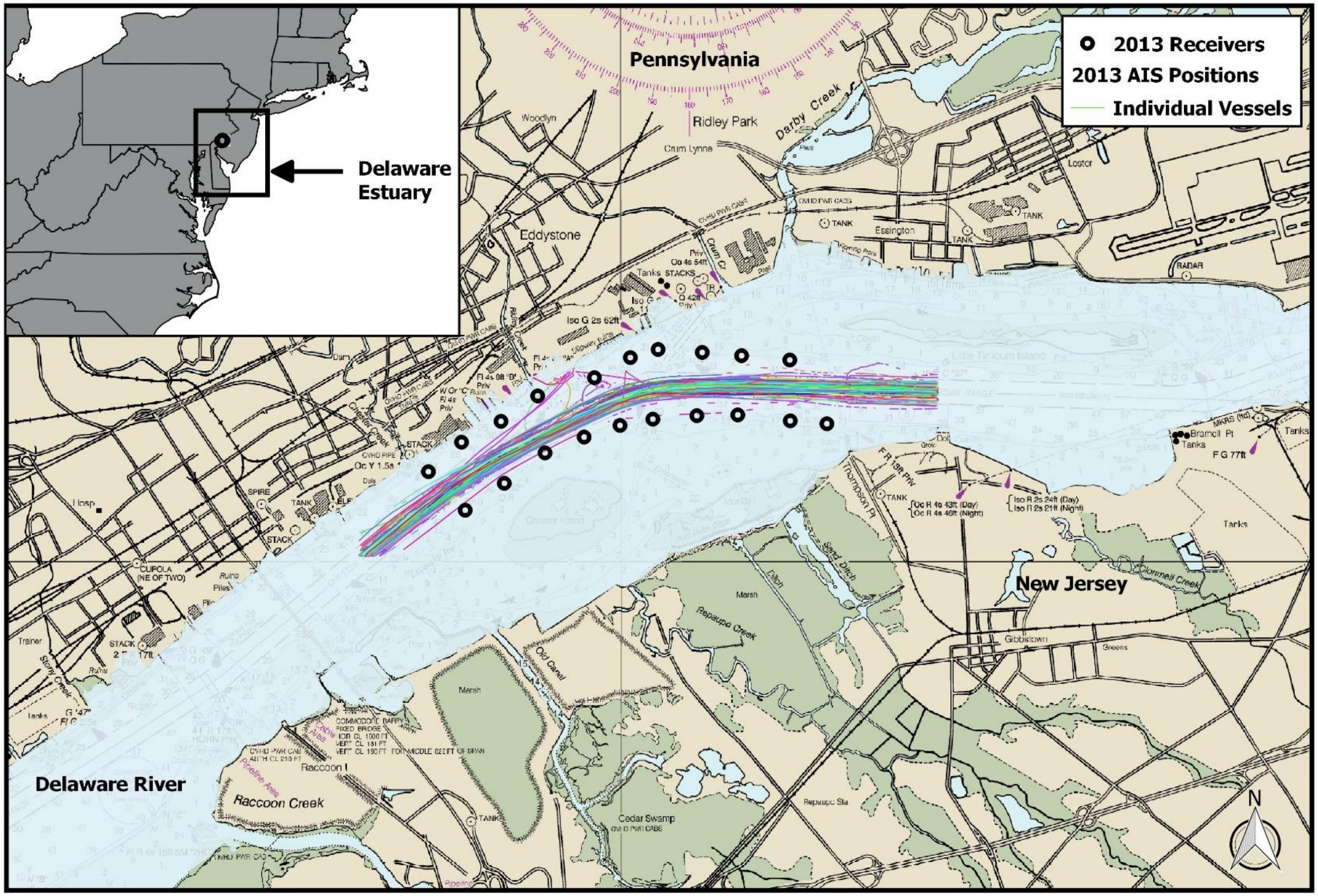

Figure 1- 4. Vessel AIS vessel traffic from July 4, 2013 – July 7, 2013 within the VPS array.

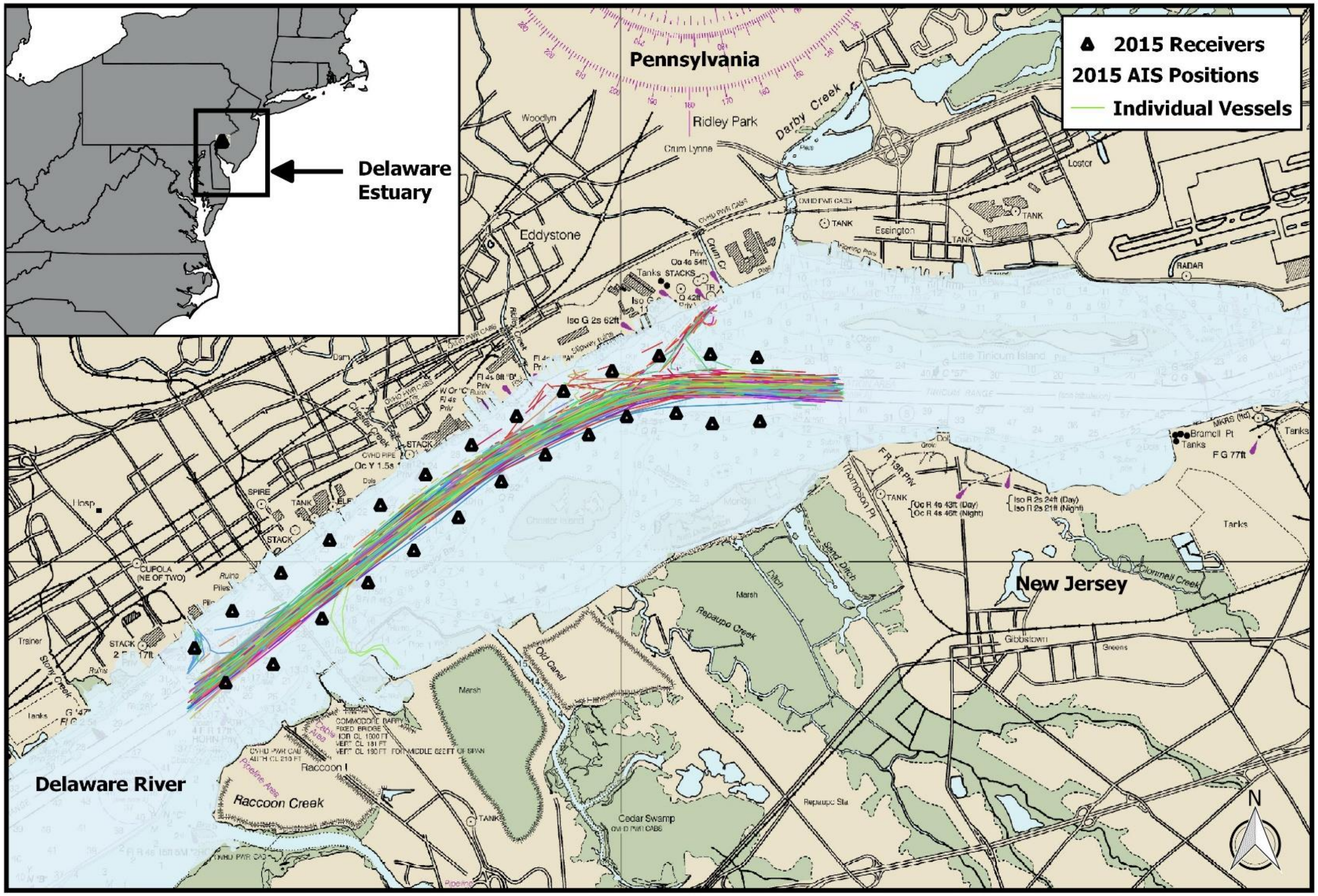

Figure 1- 5. Vessel AIS vessel traffic from July 4, 2015 – July 7, 2015 within the VPS array.

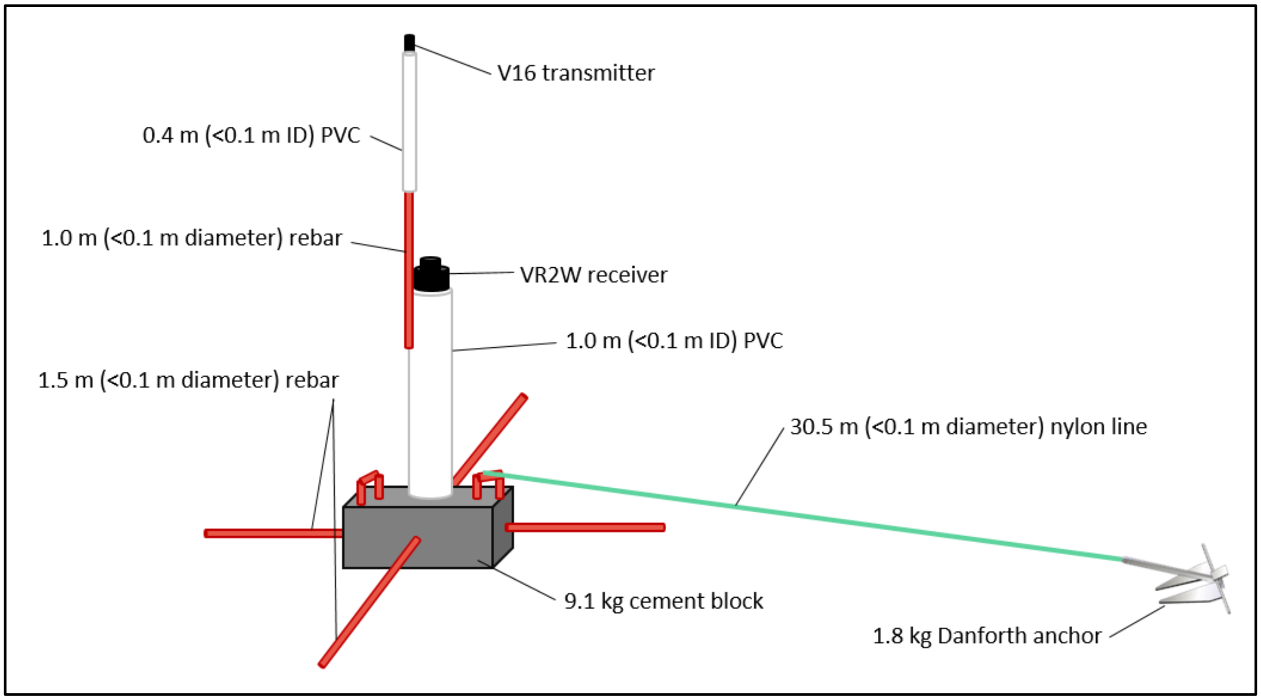

Figure 1- 6. Mooring structure used to house acoustic receiver and synchronization transmitter while promoting stability within a reach of the Delaware River. In the 2015 field season, perpendicular 1.5 m rebar used for stability were removed.

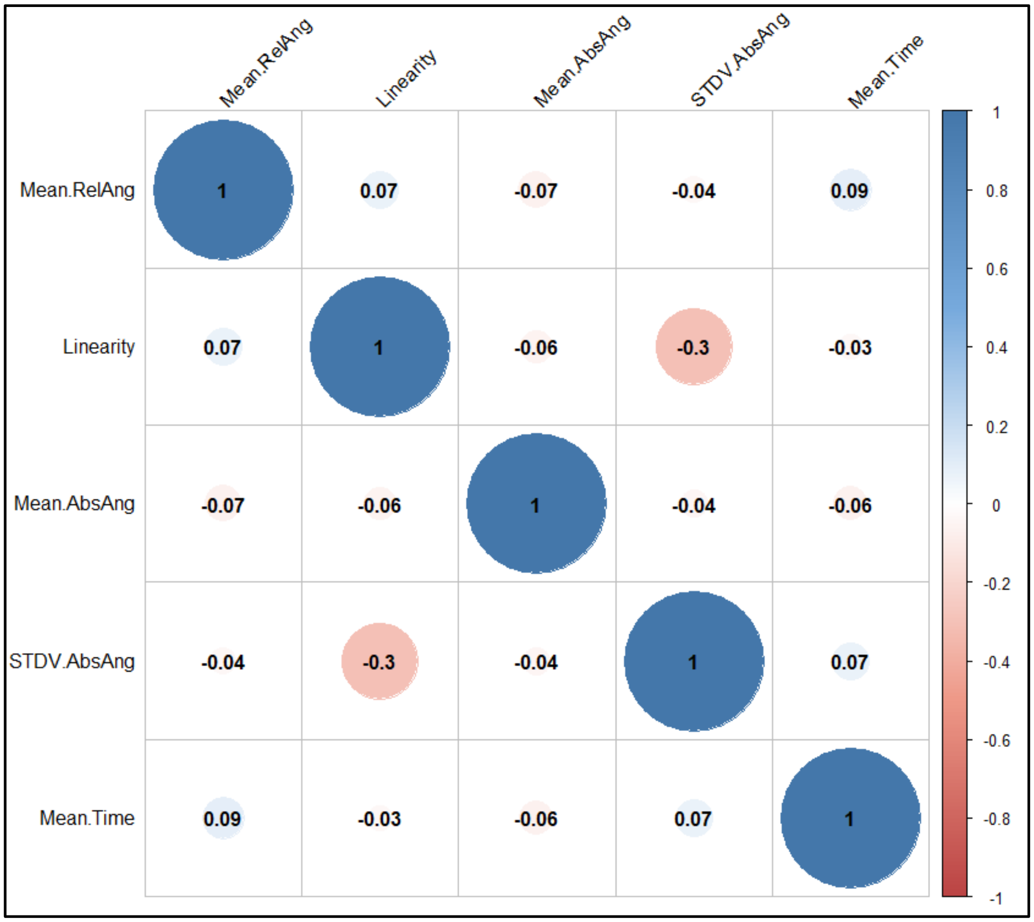

Figure 1- 7. Correlation matrix of dependent movement variables of Delaware River adult Atlantic Sturgeon in 2013 and 2015 used for trajectory clustering analysis. For each trajectory burst, non-correlated variables include Mean.RelAng = mean relative (turning) angle, Linearity = linearity ratio (distance between first and last positions divided by total distance), Mean.AbsAng = mean absolute angle (angle between x direction and the next step of relocation), STDV.AbsAng = standard deviation of absolute angle (angle between x direction and the next step of relocation), and Mean.Time = mean time. Relative circle size relates to the correlation coefficient with larger circles equaling a higher correlation and the numeric values within these circles indicated the percent correlation.

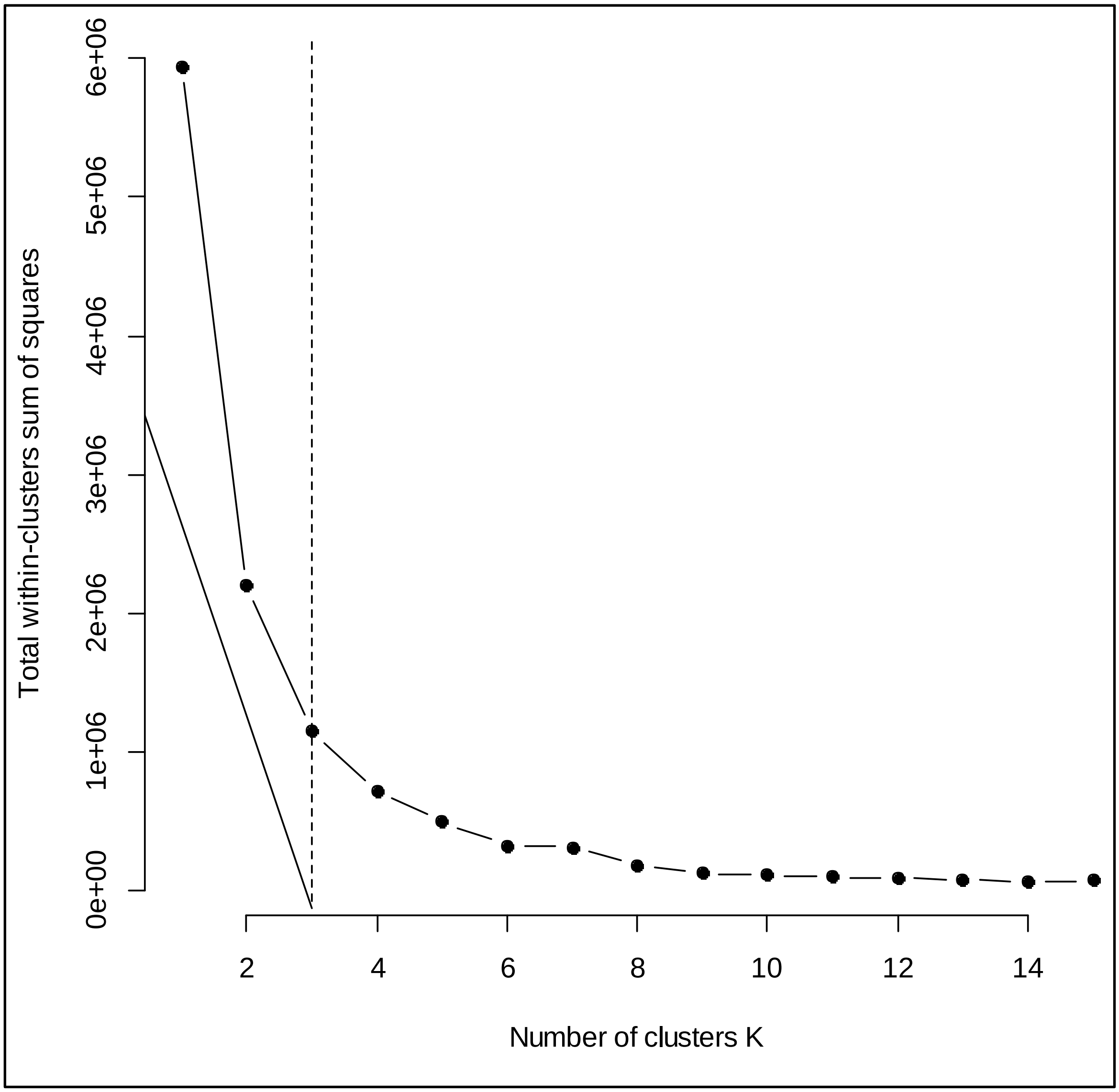

Figure 1- 8. Number of data clusters (K) plotted versus the total sum of squares (WSS) within clusters data clusters using dependent movement variables (linearity, mean time, mean relative angle, mean absolute angle, standard deviation of absolute angle) of telemetered adult Atlantic Sturgeon within the Delaware River in 2013 and 2015. The Elbow Method illustrates the point of diminishing returns between vertices at three data cluster, identified by hyphenated vertical line.

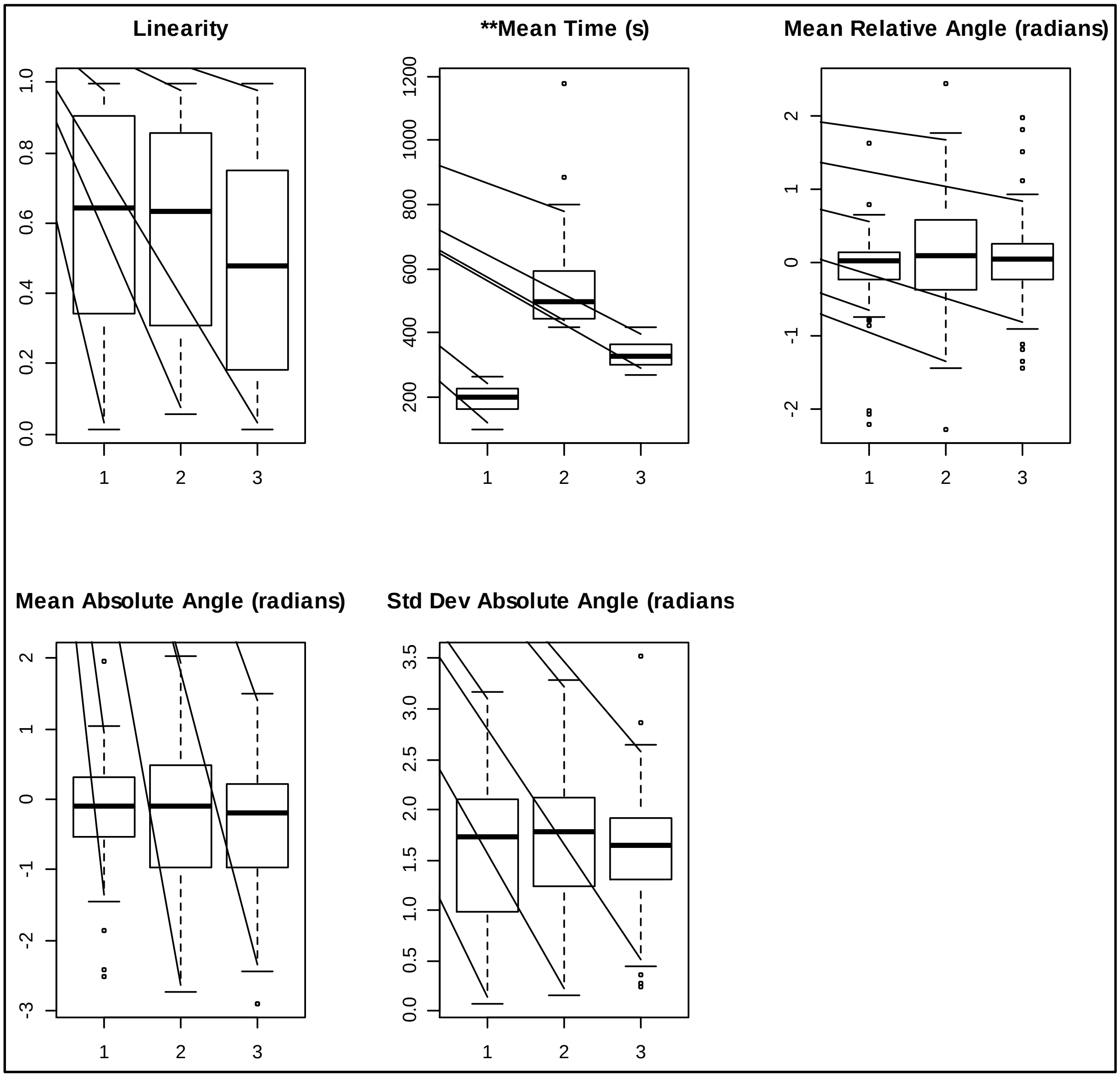

Figure 1- 9. Movement variables used in the determination of movement types of Delaware River adult Atlantic Sturgeon in 2013 and 2015. The x-axis indicated movement types I, II, and III respectively. (**) denotes significance at α = 0.05.

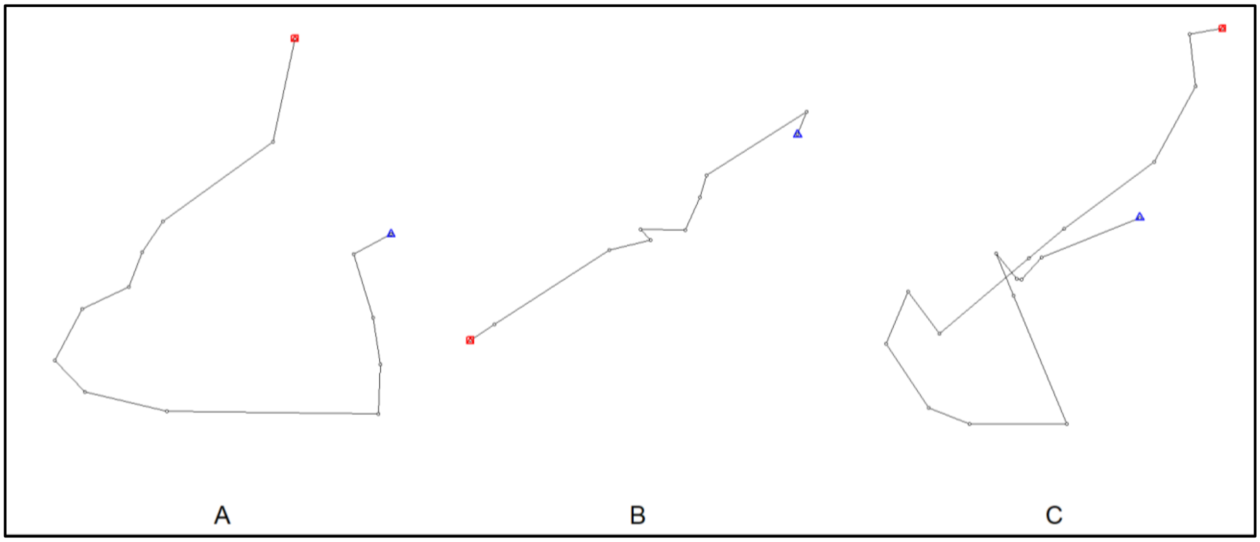

Figure 1- 10. Representative adult Atlantic Sturgeon trajectory bursts of from 2013 and 2015 for each of three defined cluster (movement) types. (A) movement type 1 is defined by short time intervals between positions (mean = 193 s); (B) movement type 2 is defined by large time intervals between position relocations (mean = 540 s) indicating continuous movement; (C) movement type 3 is defined moderate time between positions (mean = 332 s).

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Chapter 2

HABITAT USE BY ADULT AND SUBADULT ATLANTIC STURGEON (*ACIPENSER OXYRINCHUS OXYRINCHUS*) IN AN AREA OF PRESUMED SPAWNING, STAGING, AND FORAGING WITHIN THE DELAWARE RIVER, USA.

CHAPTER 2: ABSTRACT

Atlantic Sturgeon (*Acipenser oxyrinchus oxyrinchus*) are known to utilize hard-bottom and coarse sediments for spawning in adults and soft-bottom sediments (e.g., muds, sands, clays) for foraging and or staging in both subadults and adults. Sediment types, used for habitat, are subject to major changes due to the deepening and maintenance of the Delaware River navigation channel by the United States Army Corps of Engineers (USACE). I used a fine-scale VEMCO Positioning System to track telemetered Atlantic Sturgeon within the Delaware River, near Chester, PA (river kilometer 130), from early spring to late summer in 2013 (five adults and two subadults) and 2015 (ten adults and 22 subadults). I ascribed sturgeon positions to sediment types to examine habitat selection. Adult Atlantic Sturgeon selected coarse grain sediments (rock/cobble/gravel) and avoided muds and sands in 2013. Subadult Atlantic Sturgeon avoided muds (with slight preferences for gravels/sands) in 2013. Adult and subadults avoided muds while slightly preferring sands and gravels in 2015. These results support previous studies which suggest that this stretch of the Delaware is suitable for staging and spawning of Atlantic Sturgeon and describes that adults prefer coarse sediments as a habitat type which dominates the shipping channel while subadults likely avoided the study area for foraging in the beginning of their occupancy time in this portion of the River. My study indicates areas of increased risk to adult and subadult Atlantic Sturgeon within the shipping channel.

CHAPTER 2: INTRODUCTION

Atlantic Sturgeon (*Acipenser oxyrinchus oxyrinchus*) are anadromous, making seasonal spawning runs from marine waters to freshwater habitats for spawning and foraging activities (Dovel and Berggren 1983; Miller 2004; McLean et al. 2014). The Atlantic Sturgeon's lifecycle is dependent on multiple salinity levels (i.e., marine, estuarine, and freshwater) and sediment (i.e. habitat) types depending on life stage (NOAA 1998). The Atlantic Sturgeon transitions from larval drift in freshwater rearing grounds (Kynard and Horgan 2002) to freshwater residency from age 0-1 and movement out of natal rivers by age 2 (McCord et al. 2007) to coastal water transition from age 2-3 (Smith 1985) to adult coastal migrations and, finally, to pre-spawning and spawning in freshwater (Dovel and Berggren 1983; Bain 1997).

Spawning requires highly oxygenated freshwater over hard-bottom sediments which are commonly found in channelized habitats between the salt front and fall line in river habitats (Borodin 1925; Leland 1968; Scott and Crossman 1973; Bain et al. 2000). Spawning runs also differ along the North American Atlantic Coast's latitudinal gradient from runs June through September in the north-Atlantic (Taylor and Litvak 2017), April through May in the mid-Atlantic (Smith 1985), and March through April in the south-Atlantic (Smith and Clugston 1997). In addition to the spring run in the mid- and south-Atlantic, a fall run between September and October has been reported (Balazik et al. 2012; Smith et al. 2015). Before the spawning run, male and female adult Atlantic Sturgeon utilize soft-bottom sands adjacent to hard-bottom sediments for staging in the Hudson River (Comer 2017), a behavior associated with a holding location sometimes located close to the spawning area, before making their run to spawning areas (Hain et al. 2002).

Habitat preference, identified when habitat types are disproportionately selected compared to available habitat and lifecycle need, is a commonality between many different species (Johnson 1980). A better understanding of habitat selection and use, especially of an endangered species, is useful to prevent further species decline. Adult Atlantic Sturgeon in the Delaware River have been shown to prefer hard-bottom and coarse habitat while subadults likely occupy soft-bottom sediments (e.g., sands) during periods of presumed foraging (Simpson 2008). These findings are supported within the intertidal region of Minas Basin, Bay of Fundy, Canada where prey drive for invertebrates inhabiting large-grain sands (soft-bottom) dictated adult Atlantic Sturgeon sediment preference (McLean et al. 2015).

Atlantic Sturgeon are benthic feeders, typically digging and suctioning to pull out worms, shrimps, and other invertebrates (Carroll and Wainwright 2003). Subadult Atlantic Sturgeon feed in river systems while adults feed on polychaete worms, shrimp, amphipods, isopods, and small fish (sand lance) (Vladykov and Greeley 1963; Johnson 1997) in estuarine and coastal environments but do not eat during spawning migrations (Murawski and Pacheco 1977). Because most rivers have limited visibility, sturgeons use olfactory, taste, chemical cues, and electroreceptors for foraging, typically over sandy sediment types (Miller 2004; McLean et al. 2014). Whether considering the ability to forage, and thus grow/mature (McLean et al. 2014), or in finding suitable habitat for egg adhesion during spawning (Gilbert 1989; Smith and Clugston 1997), habitat availability is critical to all stages of life for Atlantic Sturgeon. Additionally, river habitats are also variable in nature with high flow events being recorded to change sediment types between only a few days' time, especially for finer sediment types (Kaeser and Litts 2010).

The Delaware River supported the largest sturgeon fishery in the United States from 1890-1899 until harvest peaked in 1890 and fell to only 6% of this peak harvest by 1901 (Secor and Waldman 1999). Since that time, the National Marine Fisheries Service (NMFS) identified five distinct Atlantic Sturgeon population segments (DPSs) along the Atlantic Coast: the Gulf of Maine (Penobscot River, Maine to the Cape Cod, Massachusetts), the New York Bight (Cape Cod, Massachusetts to the Delmarva Peninsula), the Chesapeake (Chesapeake Bay and its tributaries), the Carolinas (Albemarle Sounds, North Carolina to Santee-Cooper River, South Carolina), and the South Atlantic (Ashepoo-Combahee-Edisto Basin, South Carolina to the St. Johns River, Florida) (USFWS and NOAA 1996; ASSRT 2007). In 2012, the NMFS listed the New York Bight and Chesapeake Bay DPSs as endangered under the ESA (USOFR 2012b).

In 2016 the NMFS designated critical habitat areas which are defined by containing physical or biological features deemed essential for species management or protection and that face a known threat, for all five DPSs (USOFR 2017). The Delaware River from the Trenton, NJ – Morrisville, PA bridge through the point of the river's discharge into the river mouth at the head of the Delaware Bay (137 total river kilometers (rkms)) was designated as critical habitat. In the Delaware River, concerns over national security, including the ability to maintain the shipping channel and other physical features potentially undermines the effectiveness of critical habitat listings (USOFR 2017). Additionally, the United States Army Corps of Engineers (USACE) has continued to deepen the navigation channel from Philadelphia, PA to the Delaware Bay in order to assure safe passage of commercial vessels through the Delaware River (USACE 2016).

Acoustic tagging studies of Atlantic Sturgeon have indicated freshwater migration of reproductively viable adults in the Delaware River between Cherry Island (rkm 100) and Marcus Hook Anchorage (rkm 130) (Simpson 2008; Fox and Breece 2010; Breece 2013). Suspected spawning activity has been confirmed via the collection of Young-of-the-Year Atlantic Sturgeon

(Shirey et al. 1999; DNREC 2009; ASMFC 2017) despite continued dredging and deepening of the navigation channel which has altered and removed sediments vital for Atlantic Sturgeon spawning (Walsh 2004).

My study examined habitat preferences of adult and subadult Atlantic Sturgeon in the Eddystone and Chester Reaches of the Delaware River. This area has been identified as a location for both spawning, staging, and foraging habitats (Shirey et al. 1999; Simpson 2008; Breece et al. 2013). It is my hope that my efforts will further assist resource managers as they struggle to recover this imperiled species while balancing economic and national security concerns.

CHAPTER 2: METHODS

Study Area

The Delaware River is the country's third largest, draining an expanse of 35,000 km^2 into Delaware Bay (Kaufman et al. 2010). The Eddystone and Chester Navigation Ranges (rkm 132-138), which have undergone a great deal of modification to facilitate commercial shipping, mostly consists of non-depositional and mixed-grain reworking sediments (Sommerfield and Madsen 2003). I chose this area due to the presence of sediments associated with staging/spawning behavior for adults and foraging behavior for subadults (Simpson 2008; Breece et al. 2013).

Acoustic Telemetry

A VEMCO Positioning System (VPS) array consisting of 20 passive hydroacoustic receivers (VEMCO, Ltd. VR2W) was deployed along the perimeter of the main shipping channel in a 5.2 km corridor (Figure 2-1) from April 13 - July 9, 2013 and expanded to 26 passive receivers between rkm 131-138 along a 6.5 km corridor from April 18 - July 9, 2015 (Figure 2-1) in the Eddystone and Chester Navigation Ranges of the Delaware River near Chester, PA (rkm 130) (Figure 2-1). The VPS array was deployed in early spring and ended in early summer in both years to best capture the entry and departure of spawning/staging adults and to capture the beginning season for foraging in subadults (Shirey et al. 1999; Simpson 2008). The study area was increased in 2015 to better account for areas of suitable spawning/staging habitat for adults as well as areas for foraging of subadults in addition to findings from 2013 which indicated that many individuals were too far south of the array which I could not position.

The VPS array utilizes acoustic information in the form of hyperbolic positioning of sound, transmitted from tagged animals to fixed receivers which are converted into distances and, eventually coordinates (Smith, 2013). These hyperbolic position calculations are estimations based on environmental conditions and acoustic triangulation; therefore, a unitless measure of error, horizontal positioning error (HPE), is calculated and ascribed to each position. In order to accurately synchronize acoustic signals between receivers, thus limiting error, each receiver was accompanied by a VEMCO transmitter (VEMCO, Ltd. V16) with a nominal transmission delay of 60 s (range = 30-90 s). Each of receiver/transmitter pair was moored by 36 kg cement blocks in order to stay upright (Figure 1-6).

Collection of Atlantic Sturgeon

Atlantic Sturgeon were collected between three and 15 km off the coast of Delaware near the Delaware/Maryland border in the Atlantic Ocean. For more detailed procedures regarding the capturing, handling, and surgeries of Atlantic Sturgeon in this area, refer to Breece et al. (2013). Additional Atlantic Sturgeon were tagged by other researchers and were identified through the Atlantic Coast Telemetry Network and asked for permission to use in this study.

Analyses

Detections

Metadata of Atlantic Sturgeon including: life stage and tag number was used to identify individuals. Each individual position was screened by HPE (< 50) for analysis (Smith 2013) before minimum sample size thresholds were established. Position estimates were imported into QGIS Geographic Information System (version 2.18.28 (2018)), georeferenced, and plotted (Figures 2-3, 2-4).

Habitat Types

I used Delaware River sediment data from Sommerfield and Madsen (2003) to identify five grain sizes (habitat types) for analysis within the VPS array: (1) sands, (2) rock/cobble/gravel, (3) muddy sands, (4) sandy muds, and (5) muds/clays (Table 2-2). I collapsed these to combine sands with muddy sands and sandy muds with muds/clays in order to form three total habitat types: (1) gravel, (2) sand, and (3) mud which were then used for further analysis. These were collapsed due to failed assumptions of the individual-based chi-square test (e.g. having a single cell with expected values of zero and having less than 20% of all cells containing less than five expected observations) in considering sediment occupancy (Dixon and Massey 1969). Habitat type proportions within the study area were calculated by sediment type in order to compare expected to observe values of sturgeon positions during the analysis and proportional areas of each sediment type were calculated.

Habitat Occupancy and Use

Atlantic Sturgeon position estimates, having been imported to QGIS, were combined with habitat types through a spatial join function in order to assign each Atlantic Sturgeon position estimate to a specific habitat type within both year's study areas. Habitat use was analyzed by chi-square test (Neu et al. 1974) and, where habitat use differed from expected habitat use (total habitat available), a Bonferroni z statistic was used in order to create Bonferroni z confidence intervals which were in turn used to determine which habitat types were used more or less frequently than expected. The null hypothesis was that there was no difference between sturgeon positions actually recorded above certain sediment types (observed) and the number of positions related to proportional sediment types (expected).

Each habitat type's area was calculated between years in order to determine if observed values differed from expected values. Due to low sample sizes for sturgeon position estimates and a relatively small proportion of the mud sediment types within the array, I combined individuals into two categories: adults and subadults. If there were no differences between subadults and adults in a given year, I combined the age classes when comparing sediment use. I chose to compare two distinct life stages rather than discard sturgeons without a minimal number of VPS spatiotemporal positions. This was done to avoid failing chi-square assumptions of having a single cell with expected values of zero and having less than 20% of all cells containing less than five expected observations (Dixon and Massey 1969). An alpha value of 0.05 was used for all statistical tests.

Successive position relocations associated with acoustic telemetry studies creates the potential for pseudoreplication, which is even more relevant for a fine-scale study such as this one wherein locations are closely spaced (Byers et al. 1984; Thomas and Taylor 1990). Positions are autocorrelated and heterogeneity is eliminated if point locations, rather than individual organisms, are considered the sampling unit for a study (Aebischer et al. 1993). Due to the inability to run an individual-based chi-square test to compare sediment occupancy, I grouped sturgeons by life stage (adult and subadult) in 2013. I grouped age classes between adults and subadults due to there being no statistical difference between them in 2015. I therefore assumed that life stages independently acted similarly in 2013 and that both age groups acted similarly in 2015 in order to avoid violating statistical assumptions of pseudoreplication in acoustic telemetry studies (Aebischer et al. 1993).

CHAPTER 2: RESULTS

Telemetry

Between April 13 and July 9, 2013 five adult and two subadult Atlantic Sturgeon were detected within the 5.2 km VPS array (Table 2-1) which, due to VPS requirements of position triangulation, were located largely in the confines of my array (Figure 2-2). Adult Atlantic Sturgeon were first located within the VPS array between April 4 and June 7, 2013 and last recorded between May 27 and June 8, 2013 while subadults were first located between April 29 and May 3, 2013 and last located between May 1 and June 28, 2013. Mean array occupancy of adults was 0.06 days (range = 0.03 – 0.09 days) while it was 0.07 days (range = 0.03 – 0.12 days) for subadults (Table 2-7).

During the second field season a total of 32 Atlantic Sturgeon (10 adults and 22 subadults) were positioned within the 6.5 km VPS (Tables 1-1, 2-8) which, similar to 2013 were also mostly located within the navigation channel, thus overlapping with mapped sediments, (Figure 2-3). Adults were first recorded between May 8 and June 12, 2015 and last recorded between May 8 and June 18, 2015 while subadults were first recorded between April 30 and July 9, 2015 and last recorded between May 2 and July 9, 2015. Mean array occupancy time for adults was 0.09 days (range = 0.01 – 0.21 days) and subadults averaged 0.03 days (range = 0.01 – 0.08 days) (Table 2-8).

Occupancy and Positioning

A total of 79 sturgeon positions were removed from analysis (37 in 2013 and 42 in 2015) due to HPE values being greater than 50. Individual adults were positioned an average of 283 times (range 16 – 851) in 2013 and an average of 206 times (range = 6 – 627) in 2015 while individual subadults averaged 232 positions estimated (range = 36 – 249) in 2013 and averaged only 22 positions (range = 4 – 95) in 2015 (Table 2-8).

Sediment Types

The 2013 VPS array sediments were composed of 1% muddy clay, 2% sandy mud, 5% muddy sand, 72% sand, and 20% rock/cobble/gravel (Table 2-3, Figure 2-1). Muddy clay only occurred under Little Tinicum Island in the array's northeastern corner and sandy mud was also mainly in the northeastern array corner (Figure 2-1). Muddy sand was only in the southwestern array and sand was abundant throughout the array but most prevalent in the northeastern section between Chester and Little Tinicum Islands (Figure 2-1). Rock/cobble/gravel was predominantly located in the center of the shipping channel by Chester Island and along the western shoreline (Figure 2-1).

In 2015, the study area sediments were comprised of 5% muddy clay, 0% sandy mud, 11% muddy sand, 55% sand, and 29% rock/cobble/gravel (Table 2-4, Figure 2-2). Muddy clay was only observed in the southwestern array corner near Marcus Hook Anchorage (Figure 2-2). Muddy sand was observed in the southern array in the middle of the shipping channel and sand was again throughout the array but mostly between Chester and Little Tinicum Islands (Figure 2-2). Rock/cobble/gravel was again located mostly within the shipping channel in the middle of the array (Figure 2-2).

Sediment Occupancy

I found that the percentage of observed sediment use was significantly different between adults and subadults in 2013 ($X^2 = 8.60$, df = 2, p-value = 0.01) and was not significant in 2015 ($X^2 = 1.01$, df = 2, p-value = 0.60) so the categories were combined for further analysis in 2015. Adult Atlantic Sturgeon significantly preferred gravels but significantly avoided muds and sands as habitat types ($X^2 = 442.32$, df = 2) and subadult Atlantic Sturgeon significantly avoided muds ($X^2 = 20.71$, df = 2) in 2013 (Table 2-5). In 2015, adult/subadult Atlantic Sturgeon significantly avoided muds and selected sands and gravels but not to a significant degree ($X^2 = 86.12$, df = 2) (Table 2-6).

CHAPTER 2: DISCUSSION

Adult and subadult Atlantic Sturgeon occupied different regions of the with adults preferred hard-bottom and coarse sediments, presumably associated with spawning (Borodin 1925; Scott and Crossman 1973) along the western and northwestern outer edges of the navigation shipping channel while subadults avoided mud without significantly using sand or hard-bottom and coarse gravel, mainly along the eastern, inner edge of the channel. Subadults did not show preference for sands in this freshwater reach as has been indicated as a preferred sediment for foraging (Johnson et al. 1997). Subadult relocations were sparse and typically indicated that individuals moving through my array during the period of deployment. I hypothesize that this was due to a lack of available prey during my study time, possibly due to regular disturbances of channel sediments reduces the amount of available benthic invertebrates (Cooper 1989; Smith and Clugston 1997). Although sand made up the largest proportion of the study area, hard-bottom gravel was abundant primarily in the channel center as is evident from maintenance blasting (USACE 2016).

Adult Atlantic Sturgeon selection of coarse grain and avoidance of fine grain sediments supports previous findings of (Dees 1961; Brownell et al. 2001; Hatin et al. 2002). These preferred coarser materials are most prevalent in the center of the navigation channel and at the entrance of Penn Terminal, a port, in Chester, PA – both of which are areas likely to be traversed by vessels. Therefore, it is plausible that adults utilized these hard-bottom and coarse areas of increased vessel traffic for staging and/or spawning while subadults possibly avoided the area due to lack of food sources as has been suggested in previous studies in the Delaware River (Simpson 2008). Since subadults did not utilize the area for staging or spawning it is more likely that these individuals, none of which had been positioned more than 100 times in a year, simply passed through my study area, acting as array transients between feeding grounds. I base this conclusion on subadult activity which showed individuals travelling completely through the array with very few positions along with previous research which indicates that subadults rarely move quickly, only doing so out of necessity (Simpson 2008).

Human modification and habitat alteration in the Delaware River impacts both adult and subadult Atlantic Sturgeon in addition to earlier life stages (e.g., egg, larval, and Young-of-the-Year) also see the effects of vessel traffic when maintenance dredging increases the level of suspended sediments which adhere to eggs and affect growth and development (Cooper 1989; Sinderman 1994; Smith and Clugston 1997). While adult sturgeon, selection for spawning substrates are more directly impacted by being forced into areas of blasting and vessel traffic, subadults are possibly indirectly affected by alterations to sediment composition which affects prey distribution. My study indicated that these life stages not only face different effects of vessel traffic but are also affected at different times. Adults enter the river in early spring while subadults enter in late spring and early summer. During the summer occupancy of subadults, individuals tend to occupy deep-water habitat outside of the shipping channel, possibly to forage without interference (Simpson 2008). For my analysis, I did not discard individuals with low numbers of spatiotemporal positions since these were all part of contiguous tracks that did not fall out of the reach of the acoustic array. Instead, I binned individual sturgeons by life stage (either adult or subadult) and also binned sediment types based on their dominant components, reducing the categories from five to three (muds, sands, gravels). Since the Delaware River's shipping channel is so well mapped due to routine maintenance dredging of the shipping channel, this study illustrates several areas wherein sediment and sturgeon relocations overlap in possible areas of impact.

Total position estimates separated by adults and subadults suggest spatial separation whereby adults are primarily found on the outer edge of the bend in the river amongst coarse grain sediments where flows and water oxygenation are highest and subadults tend to use the inner portion of the river bend characterized by finer grain materials. This combination of higher flow, previously identified as a significant physical characteristic of potential spawning areas (Borodin 1925; Leland 1968), sediments consisting of mostly sand and gravel, and increased spatiotemporal positions of adult Atlantic Sturgeon indicates that the outer edge of the channel along Chester, PA, specifically near Penn Terminal as well as in the middle-array section near the mouth of Chester Creek, are likely locations for sturgeon staging or spawning.

Due to the high proportion of hard-bottom and coarse substrate within the center of the shipping channel and in the southern portion of the study area, just south of Chester, PA, my findings provide further evidence of the risk of vessel strikes for adult Atlantic Sturgeon within the freshwater reaches of the Delaware River. Rather than focus solely on altering shipping traffic, resources managers could consider the possibility of adding artificial hard-bottom and coarse sediments to recreate preferred spawning locations outside of areas associated with high vessel traffic. These areas of artificial spawning habitat would also need to meet the basic salinity, flow, and dissolved oxygen requirements for the species. Remediation plans like this require careful consideration of the natural process of river siltation, especially in areas of greater depth and high water flow (Bennion and Manny 2014).

Resources managers can also use my findings of hard-bottom and coarse sediment preference by adult Atlantic Sturgeon and the avoidance of subadults to soft-bottom sediments to map other, similar systems. This is especially relevant when considering river systems with very few individuals to monitor. The USACE's blasting of hard-bottom sediments has already been confined to winter months, where both adults and subadults are less likely to be present within areas of presumed spawning. Despite this, dredging efforts, wherein smaller individuals are subjected to possible entrainment (ASSRT 2007) and altered sediment composition is more likely affect habitat selection of all sturgeon life stages, were recorded in my study area during spring and summer of 2015. I'd encourage resources managers to use this information to further limit channel maintenance to specific portions of the channel during the already defined spawning location and time. My study built upon previous work (Shirey et al. 1999; Simpson 2008) in this system that identified these areas of importance and I would like to suggest that an examination of the area be undertaken following the end of the USACE Delaware River deepening project. In doing so, managers will be able to judge the impacts of a large-scale federal dredging project on important habitats for adult and subadult Atlantic Sturgeon. As more sections of Atlantic Sturgeon spawning and foraging habitats are mapped, more concerted conservation efforts can be put in place. As has done with the West Indian Manatee (*Trichechus* *manatus latirostris*) in Florida (Calleson and Frohlich 2007), mandatory restrictions to specific areas, even if it's just outside of the shipping channel, can successfully protect species.

In conclusion, this study illustrates evidence of habitat preferences of adult and subadult Atlantic Sturgeon within a small stretch of the Delaware River. It is evident from both occupancy and number of spatiotemporal positions provided by each individual, that adult Atlantic Sturgeon use the Eddystone and Chester Ranges of the Delaware River for its hard-bottom and coarse sediment, linked to staging and spawning behavior, while subadults only travel through the area and likely did not use the area for foraging during the early portion of their summer foraging timeline. My study time did not overlap with the majority of proposed subadult occupancy for foraging so this interpretation is limited to the beginning of subadult habitat use for foraging in this portion of the Delaware River. It is my hope that my findings can aid resources managers' understanding of both habitat use and vessel strike risk assessment in the Delaware River and provide options for balancing economic progress with species conservation.

Table 2- 1. Summary of adult and subadult Atlantic Sturgeon tag number, associated research institute of tag, date tagged, length (FL/TL), sex, and total number of positions estimates in both study years (2013/2015) appearing within the VPS array.

Tag ID Number	Organization	Release Date	FL (cm)	TL (cm)	Life Stage	Sex	Position Estimates	
							2013	2015
11615	DSU	4/5/2009	176	203	Adult	Male	16	-
20458	DSU	4/25/2011	186	211	Adult	Unknown	-	9
46237	DSU	4/2/2011	208	230	Adult	Female	851	11
48761	DSU	4/12/2010	184	208	Adult	Male	55	-
48763	DSU	4/12/2010	196	223	Adult	Female	-	128
48785	DSU	4/22/2010	206	230	Adult	Female	434	24
25370	DSU	4/26/2014	191	210	Adult	Male	-	53
26428	DSU	4/12/2014	174	196	Adult	Male	-	430
27520	DSU	4/26/2013	177	201	Adult	Unknown	-	627
30447	DSU	4/3/2012	167	188	Adult	Male	-	364
30469	DSU	4/9/2012	208	233	Adult	Female	-	405
30494	DSU	4/17/2012	172	193	Adult	Female	84	6
19352	ERC	6/28/2011	713	828	Subadult	Unknown	-	12
19353	ERC	5/12/2011	586	686	Subadult	Unknown	-	37
61436	ERC	8/18/2009	673	791	Subadult	Unknown	-	52
20173	ERC	10/16/2014	269	315	Subadult	Unknown	-	8
20178	ERC	11/23/2014	325	377	Subadult	Unknown	-	9
20180	ERC	12/3/2014	311	355	Subadult	Unknown	-	34
23395	ERC	12/4/2014	360	422	Subadult	Unknown	-	37
29702	DE DFW	11/25/2014	35	41	Subadult	Unknown	-	10
32504	DSU		103	116	Subadult	Unknown	-	5
23936	VIMS	4/21/2015	87	102	Subadult	Unknown	-	7
23938	VIMS	4/18/2015	76	88	Subadult	Unknown	-	16

Tag ID Number	Organization	Release Date	FL (cm)	TL (cm)	Life Stage	Sex	Position Estimates	
							2013	2015
23942	VIMS	3/31/2015	68	78	Subadult	Unknown	-	10
26374	VIMS	5/7/2014	69	80	Subadult	Unknown	-	16
26382	VIMS	4/18/2014	70	76	Subadult	Unknown	-	5
26383	VIMS	4/18/2014	71	80	Subadult	Unknown	-	42
26392	VIMS	3/28/2014	73	85	Subadult	Unknown	-	95
26393	VIMS	4/1/2014	62	72	Subadult	Unknown	-	5
26397	VIMS	2/25/2014	69	80	Subadult	Unknown	-	5
26401	VIMS	2/25/2014	68	79	Subadult	Unknown	-	4
26409	VIMS	3/28/2014	71	82	Subadult	Unknown	-	10
26412	VIMS	4/9/2014	93	74	Subadult	Unknown	-	49
30079	SBU	5/2/2012	-	91	Subadult	Unknown	36	-
12518	VIMS	4/4/2015	84	95	Subadult	Unknown	-	5
14567	CT DEEP	7/31/2012	70	80	Subadult	Unknown	429	-

Table 2- 2. Sediment type categories within 2013 and 2015 VPS arrays (Sommerfield and Madsen 2003).

Grain Size Class	Dominant	Subdominant
Muddy Clay	Mud	<10% sand and <10% gravel
Sandy Mud	Mud	>10% sand (sand > gravel)
Muddy Sand	Sand	>10% mud (mud > gravel)
Sand	Sand	<10% mud and <10% gravel
Rock/Cobble/Gravel	Gravel	<10% sand and <10% mud

Table 2- 3. Habitat/sediment classification of the Eddystone and Chester Ranges of the Delaware River shipping channel in 2013 (Sommerfield and Madsen 2003). [1]Muddy Clay/Sandy Mud and [2]Muddy Sand/Sand were combined.

Habitat Type	Total Area Per Habitat Type (km^2)	Proportion of Total Area (P_{io})
[1]Muddy Clay	0.3	0.01
[1]Sandy Mud	0.8	0.02
[2]Muddy Sand	1.8	0.05
[2]Sand	27.4	0.72
[3]Rock/Cobble/Gravel	7.7	0.20
Totals	38.0	1.00

Table 2- 4. Habitat/sediment classification of the Eddystone and Chester Ranges of the Delaware River shipping channel in 2015 (Sommerfield and Madsen 2003). [1]Muddy Clay/Sandy Mud and [2]Muddy Sand/Sand were combined.

Habitat Type	Total Area Per Habitat Type (km^2)	Proportion of Total Area (P_{io})
[1]Muddy Clay	2.6	0.05
[1]Sandy Mud	0.0	0.00
[2]Muddy Sand	5.8	0.11
[2]Sand	27.4	0.55
[3]Rock/Cobble/Gravel	14.5	0.29
Totals	50.3	1.00

Table 2- 5. Atlantic Sturgeon habitat use analysis within the Eddystone and Chester Ranges of the Delaware River in 2013. (**) denotes statistical significance at α = 0.05.

Habitat Type	Percent of Area Per Habitat Type	Observed Atlantic Sturgeon	Expected Atlantic Sturgeon	Percentage Observed Atlantic Sturgeon in each Habitat Type (Pi)
		Adults		
Muds	2.8%	5**	31	0.4%
Sands	76.9%	610**	858	54.7%
Gravels	20.4%	501**	227	44.9%
Totals	100.0%	1116	1116	100.0%
		Subadults		
Muds	2.8%	0**	12	0.0%
Sands	76.9%	327	338	74.3%
Gravels	20.4%	113	90	25.7%
Totals	100.0%	440	440	100.0%

Table 2- 6. Atlantic Sturgeon habitat use analysis within the Eddystone and Chester Ranges of the Delaware River in 2015. (**) denotes statistical significance at $\alpha = 0.05$.

Habitat Type	Percent of Area Per Habitat Type	Observed Atlantic Sturgeon	Expected Atlantic Sturgeon	Percentage Observed Atlantic Sturgeon in each Habitat Type (Pi)
Adults & Subadults				
Muds	5.1%	20**	119	1.0%
Sands	66.0%	1587	1536	67.3%
Gravels	28.9%	719	671	31.7%
Totals	100.0%	2326	2326	100.0%

Table 2- 7. Detection frequency of acoustically tagged adult and subadult Atlantic Sturgeon within the Delaware River indicating how many times each individual was positioned, total days in which each sturgeon was positioned within the array, the array occupancy (days present divided by total array days), the first and last date time, and the number of total trajectory bursts recorded in 2013. The sum, mean, and standard deviation (STDV) were also calculated.

Transmitter	Detection Frequency	Unique Days in Array	Occupancy (Days)	Date Entered	Date Departed
			Adult		
11615	15	2	0.03	6/7/2013	6/8/2013
46237	851	7	0.09	5/22/2013	5/28/2013
48761	57	3	0.04	4/29/2013	5/27/2013
48785	413	4	0.05	5/24/2013	5/31/2013
30494	85	4	0.05	5/2/2013	6/8/2013
Sum	**1421**	**20**	**0.26**		
Mean	**269.43**	**4.43**	**0.06**	**5/17/2013**	**6/1/2013**
STDV	**354.13**	**1.87**	**0.02**		
			Subadult		
30079	36	2	0.03	4/29/2013	5/1/2013
14567	429	9	0.12	5/3/2013	6/28/2013
Sum	**465**	**11**	**0.14**		
Mean	**232.50**	**5.50**	**0.07**	**5/1/2013**	**5/30/2013**
STDV	**277.89**	**4.95**	**0.06**		

Table 2- 8. Detection frequency of acoustically tagged adult and subadult Atlantic Sturgeon within the Delaware River indicating how many times each individual was positioned, total days in which each sturgeon was positioned within the array, the array occupancy (days present divided by total array days), the first and last date time, and the number of total trajectory bursts recorded in 2015. The sum, mean, and standard deviation (STDV) were also calculated.

Transmitter	Detection Frequency	Unique Days in Array	Occupancy (Days)	Date Entered	Date Departed
			Adult		
20458	9	1	0.01	6/1/2015	6/1/2015
46237	11	2	0.03	5/18/2015	5/21/2015
48763	128	4	0.05	5/17/2015	5/20/2015
48785	24	4	0.05	5/31/2015	6/10/2015
25370	53	4	0.05	6/12/2015	6/18/2015
26428	430	12	0.16	5/14/2015	6/6/2015
27520	628	16	0.21	5/14/2015	6/10/2015
30447	365	12	0.16	5/14/2015	5/29/2015
30469	406	10	0.13	5/11/2015	5/20/2015
30494	6	1	0.01	5/8/2015	5/8/2015
Sum	**2060**	**66**	**0.86**		
Mean	**206.00**	**6.60**	**0.09**	**5/20/2015**	**5/29/2015**
STDV	**229.25**	**5.40**	**0.07**		
			Subadult		
19352	12	1	0.01	6/6/2015	6/6/2015
19353	37	2	0.03	4/30/2015	5/22/2015
61436	52	2	0.03	5/27/2015	5/28/2015
20173	8	2	0.03	5/8/2015	5/8/2015
20178	9	1	0.01	5/10/2015	5/10/2015
20180	34	4	0.05	5/24/2015	6/3/2015

Transmitter	Detection Frequency	Unique Days in Array	Occupancy (Days)	Date Entered	Date Departed
			Subadult		
23395	37	3	0.04	4/30/2015	5/2/2015
29702	10	3	0.04	5/1/2015	5/16/2015
32504	5	1	0.01	6/29/2015	6/29/2015
23936	7	1	0.01	7/1/2015	7/1/2015
23938	16	3	0.04	5/18/2015	5/26/2015
23942	10	1	0.01	6/10/2015	6/10/2015
26374	16	2	0.03	6/12/2015	6/30/2015
26382	5	1	0.01	5/21/2015	5/21/2015
26383	42	3	0.04	5/19/2015	6/29/2015
26392	95	6	0.08	5/27/2015	7/4/2015
26393	5	1	0.01	6/6/2015	6/6/2015
26397	5	1	0.01	6/22/2015	6/22/2015
26401	4	1	0.01	6/2/2015	6/2/2015
26409	10	1	0.01	7/9/2015	7/9/2015
26412	49	4	0.05	5/21/2015	6/26/2015
12518	5	1	0.01	5/15/2015	5/15/2015
Sum	**473**	**45**	**0.58**		
Mean	**21.50**	**2.05**	**0.03**	**5/28/2015**	**6/6/2015**
STDV	**22.79**	**1.36**	**0.02**		

Table 2- 9. Summary of total array occupancy and number of detections of subadult Atlantic Sturgeon in 2013 and 2015. The mean and standard error were also calculated for occupancy and number of detections in each year.

	Occupancy		Detections	
Year	Mean (Range)	Standard Error	Mean (Range)	Standard Error
2013 (n=2)	0.07 days (0.03-0.12 days)	0.05	232 (36-249)	196.5
2015 (n=22)	0.03 days (0.01-0.081 days)	<0.01	22 (4-95)	4.9

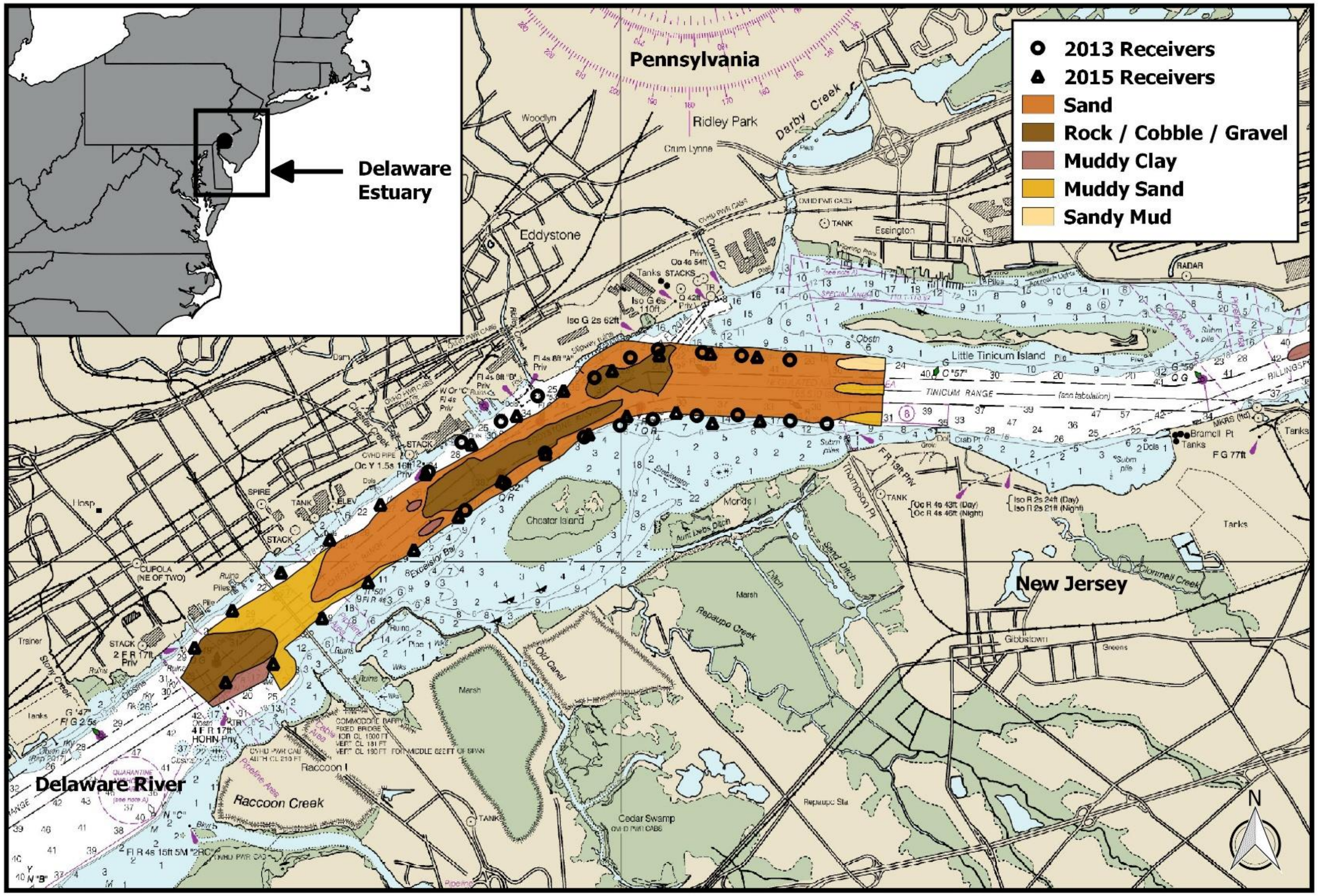

Figure 2- 1. 2013 and 2015 study site of VPS arrays: Delaware River bathymetry with sediment types near Chester, PA. Inset details locations of VEMCO, Ltd. VR-2W hydroacoustic receivers and accompanying transmitter tags.

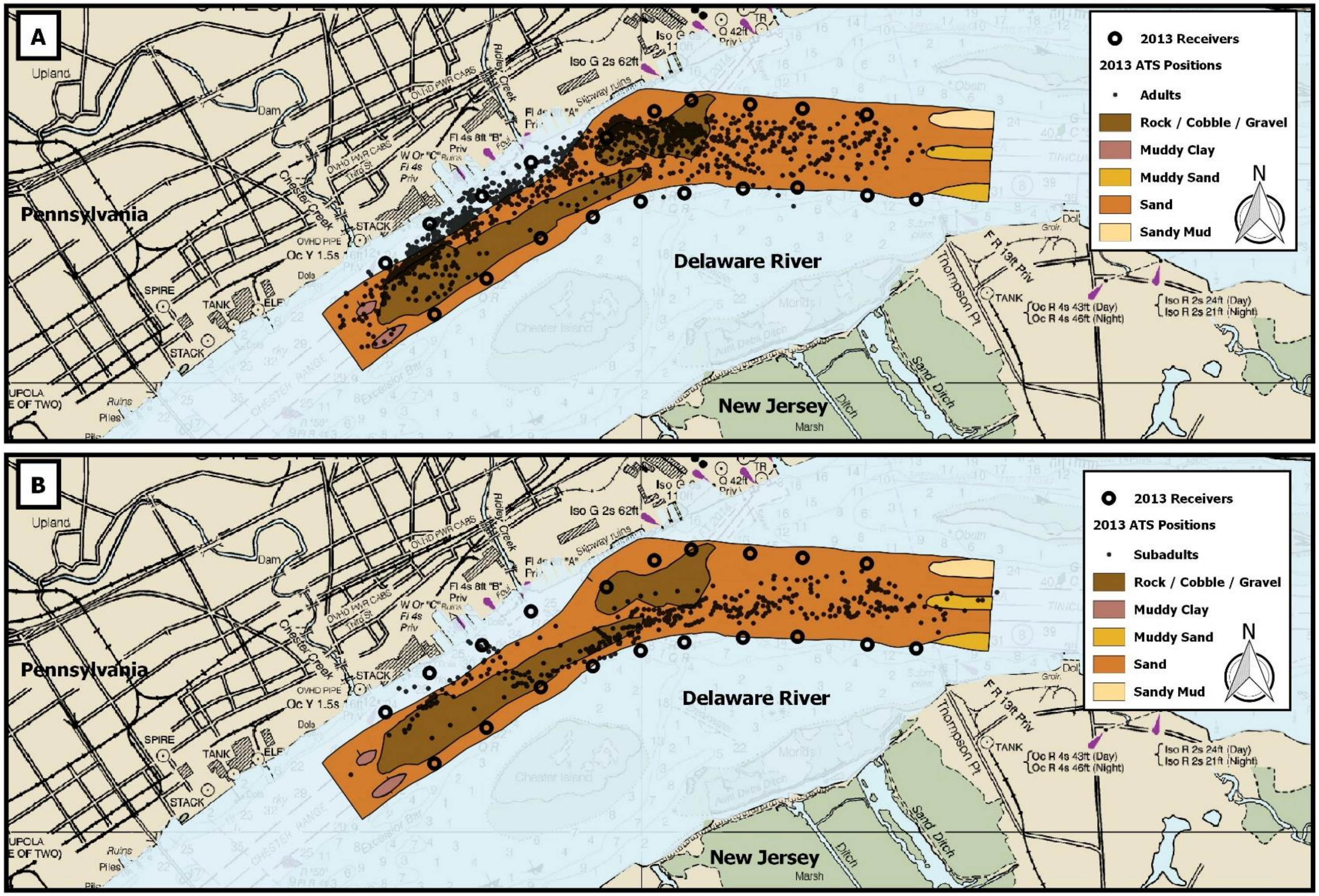

Figure 2- 2. 2013 VPS array overlaid with adult (A) and subadult (B) Atlantic Sturgeon position estimates and sediment types.

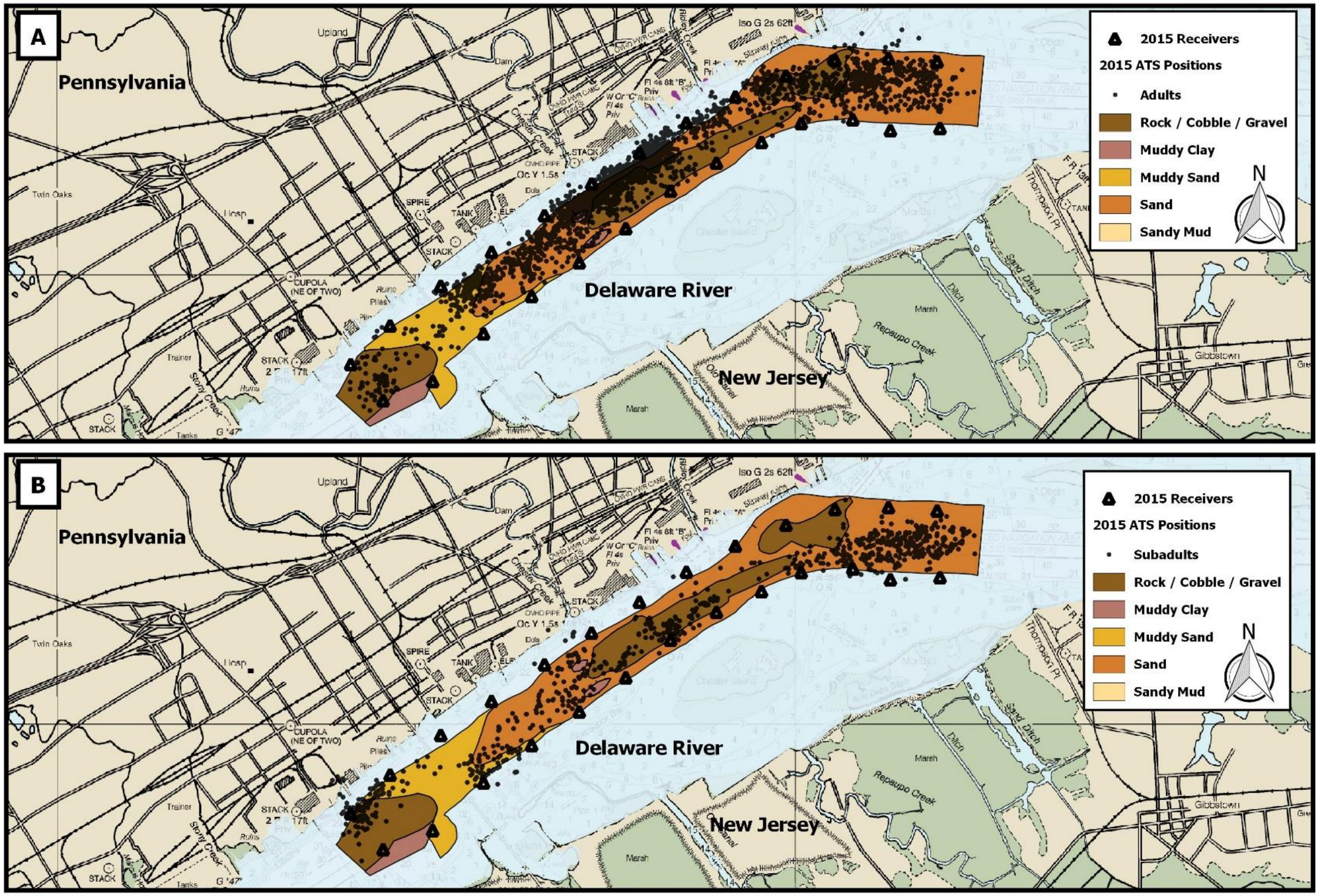

Figure 2- 3. 2015 VPS array overlaid with adult (A) and subadult (B) Atlantic Sturgeon position estimates and sediment types.

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